A Brief Overview of Results from the 1st LHC Heavy Ion Run

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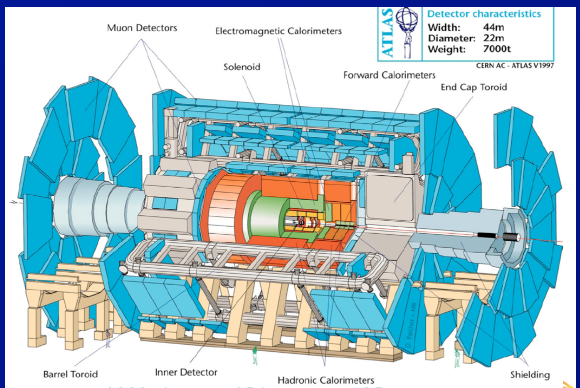
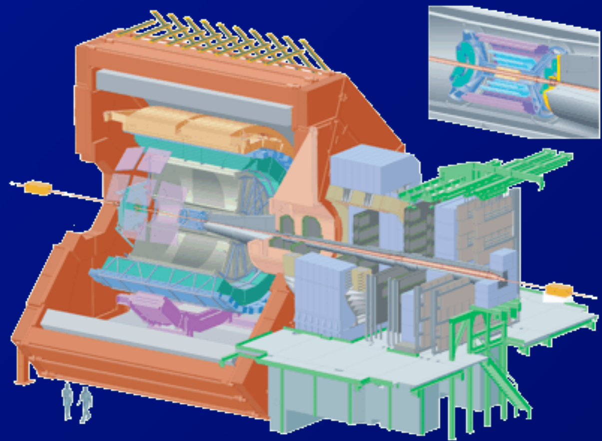
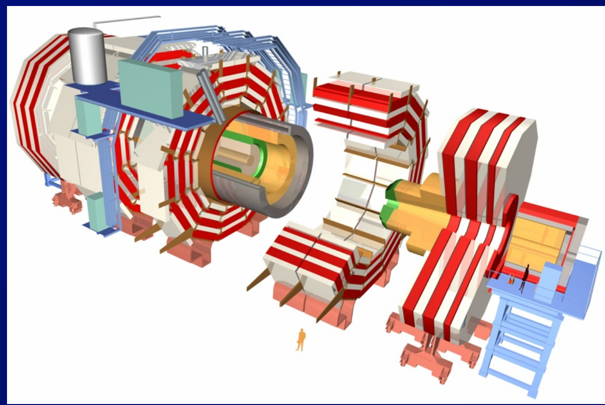






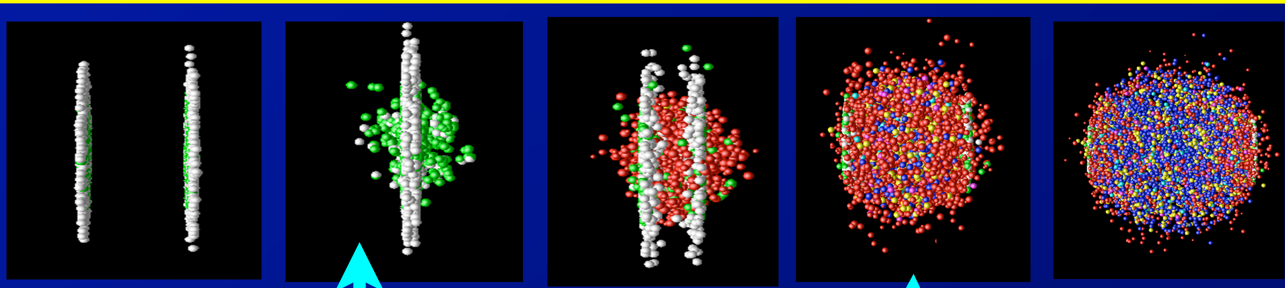
Material liberally drawn from QM 2011 talks by:

Steinberg, Wyslouch, Velkovska, Jia, Snellings, Krajczar, Loizides, Truzpek, Lee, Appelhauser, Heinz, BAC

LHC Heavy Ion Pre-history (1 year ago)

From BAC ICHEP 2010 Plenary Talk

Pb+Pb (Canonical) Time History



Initial entropy (gluon) production

Rapid Thermalization

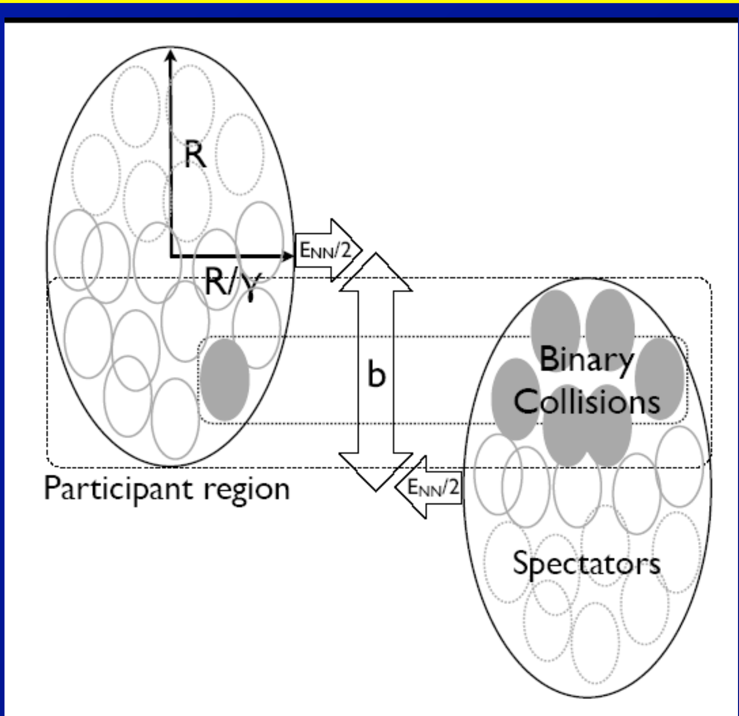
Collective Evolution

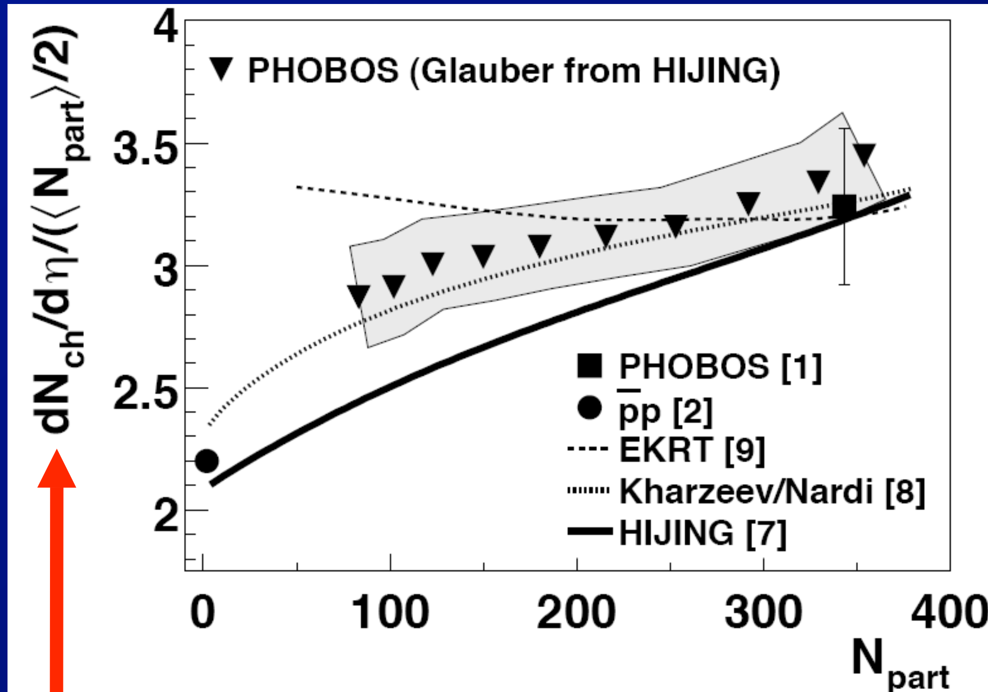
Hadronization

- Three questions for which first Pb+Pb run at LHC will provide insight
  - What physics drives the initial entropy production? ✔
  - Will quark gluon plasma at the LHC remain strongly coupled, do we understand collectivity at RHIC? ✔
  - What is the physics responsible for Jet quenching? ✔

+ much more

RHIC Particle Multiplicities

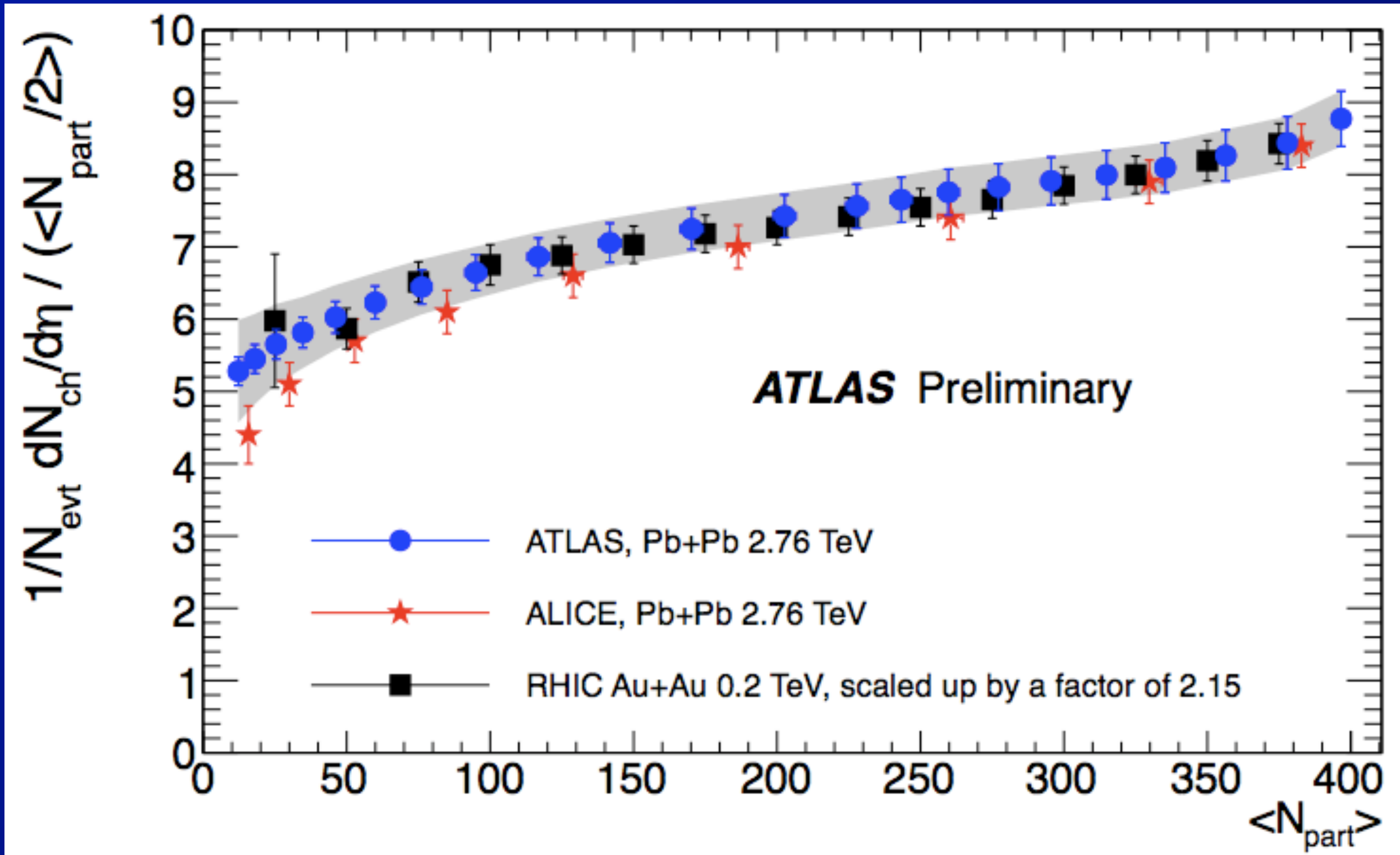




Multiplicity per colliding nucleon pair

- Multiplicity @ RHIC on low end of predicted range, slow growth with N_{part}
  - Suppression of expected hard contribution
    - ⇒“Saturation” via gluon recombination?
    - ⇒Test by going to LHC where saturation effects are expected to be stronger.

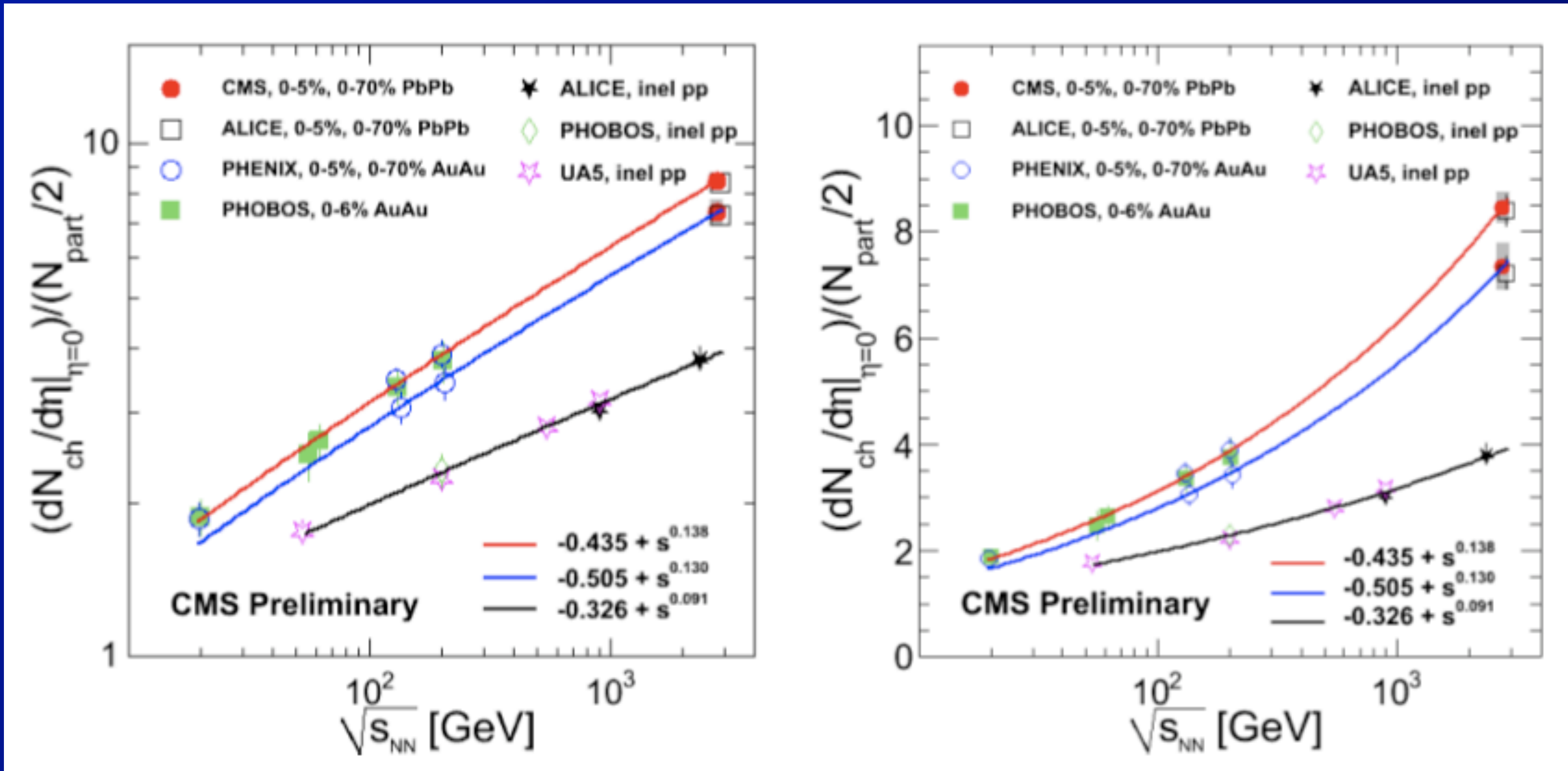
Charged Particle Multiplicity



- Weak variation of $dN_{chg}/d\eta$ with centrality
  - Consistent results between ALICE, ATLAS, CMS
- Same centrality variation @ RHIC and LHC

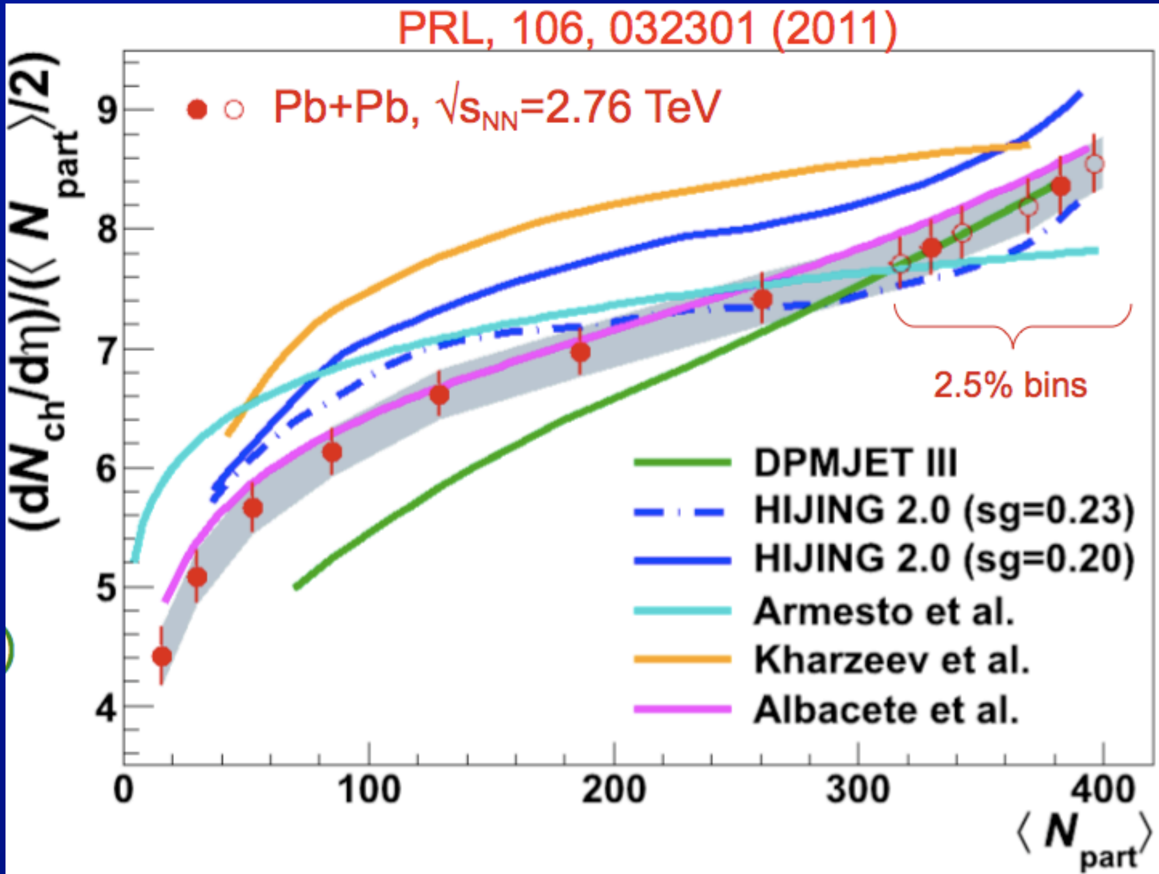
  ⇒(Naturally) consistent with saturation?

Charged Particle Multiplicity (2)



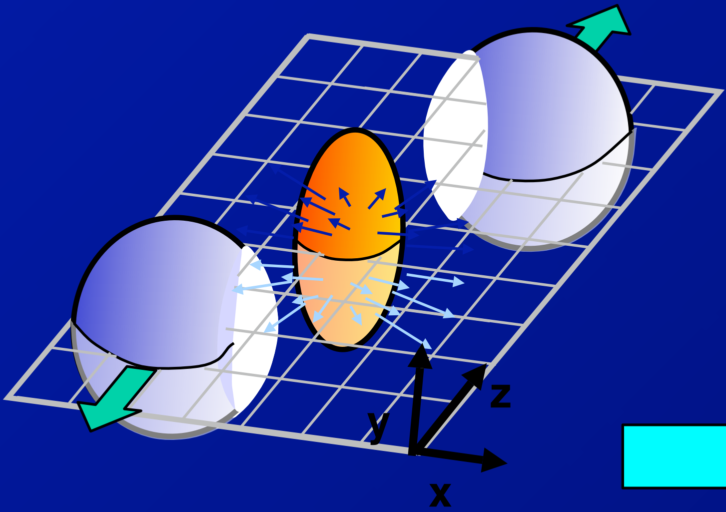
- Above 10 GeV, mid-rapidity $dN_{chg}/d\eta$ varies as a power law in s_{NN} for both central, min-bias
  - ⇒ALICE: power = 0.15
  - ⇒CMS: power = 0.13

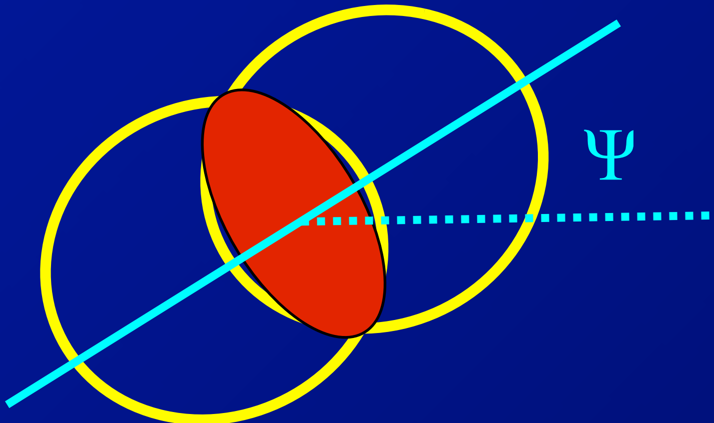
Charged Particle Multiplicity (3)

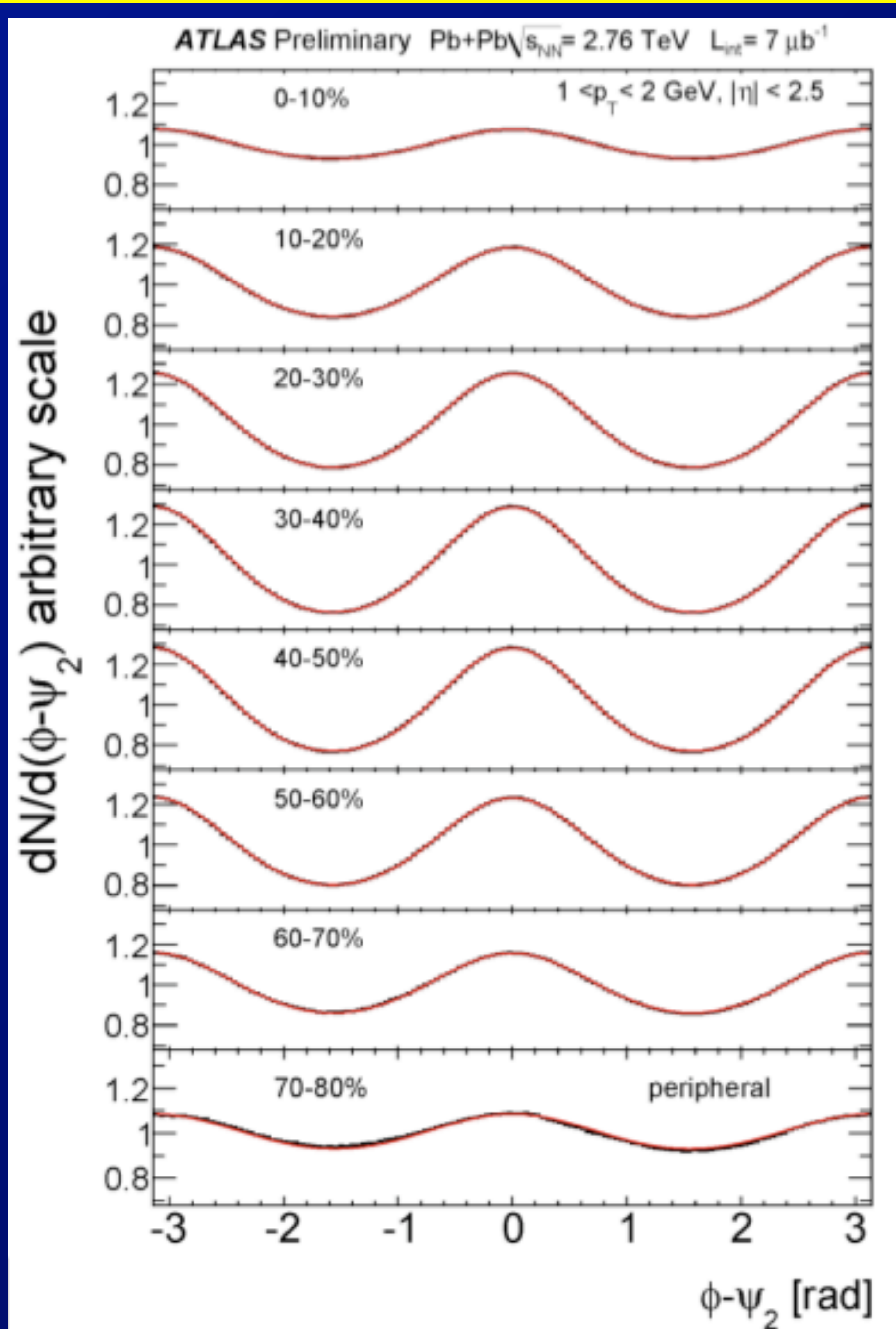


- Generically, saturation models too flat in more central collisions ($300 < N_{part} < 400$)
  - ⇒Except for Albacete *et al*
- Soft + hard *a la* HIJING 2.0 can also describe the N_{part} dependence of $dN_{chg}/d\eta$

Collective Motion: Elliptic Flow

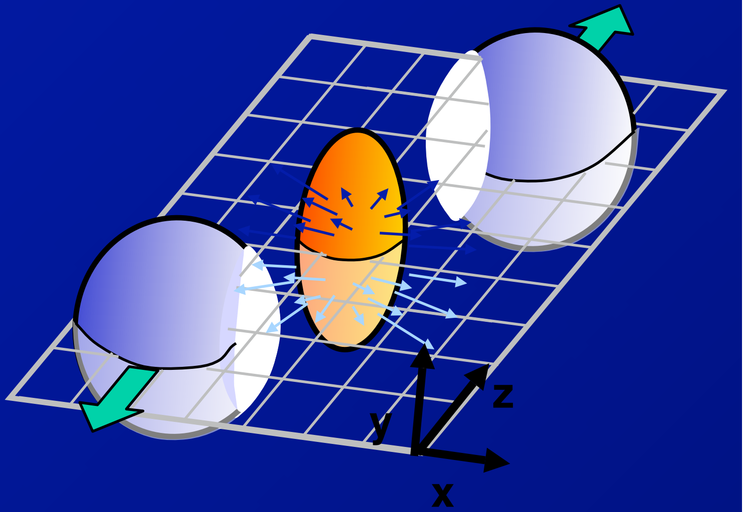


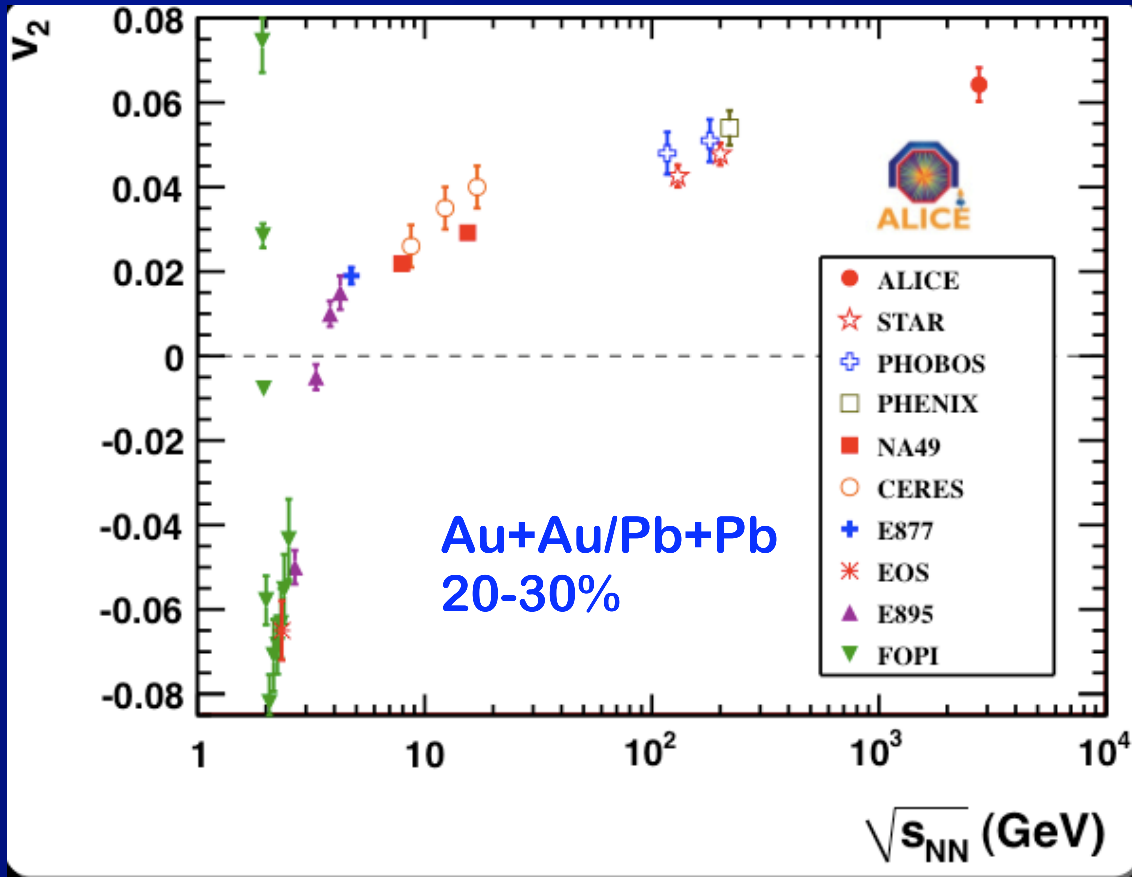




- Pressure converts spatial anisotropy to momentum anisotropy.

Collectivity: Elliptic Flow

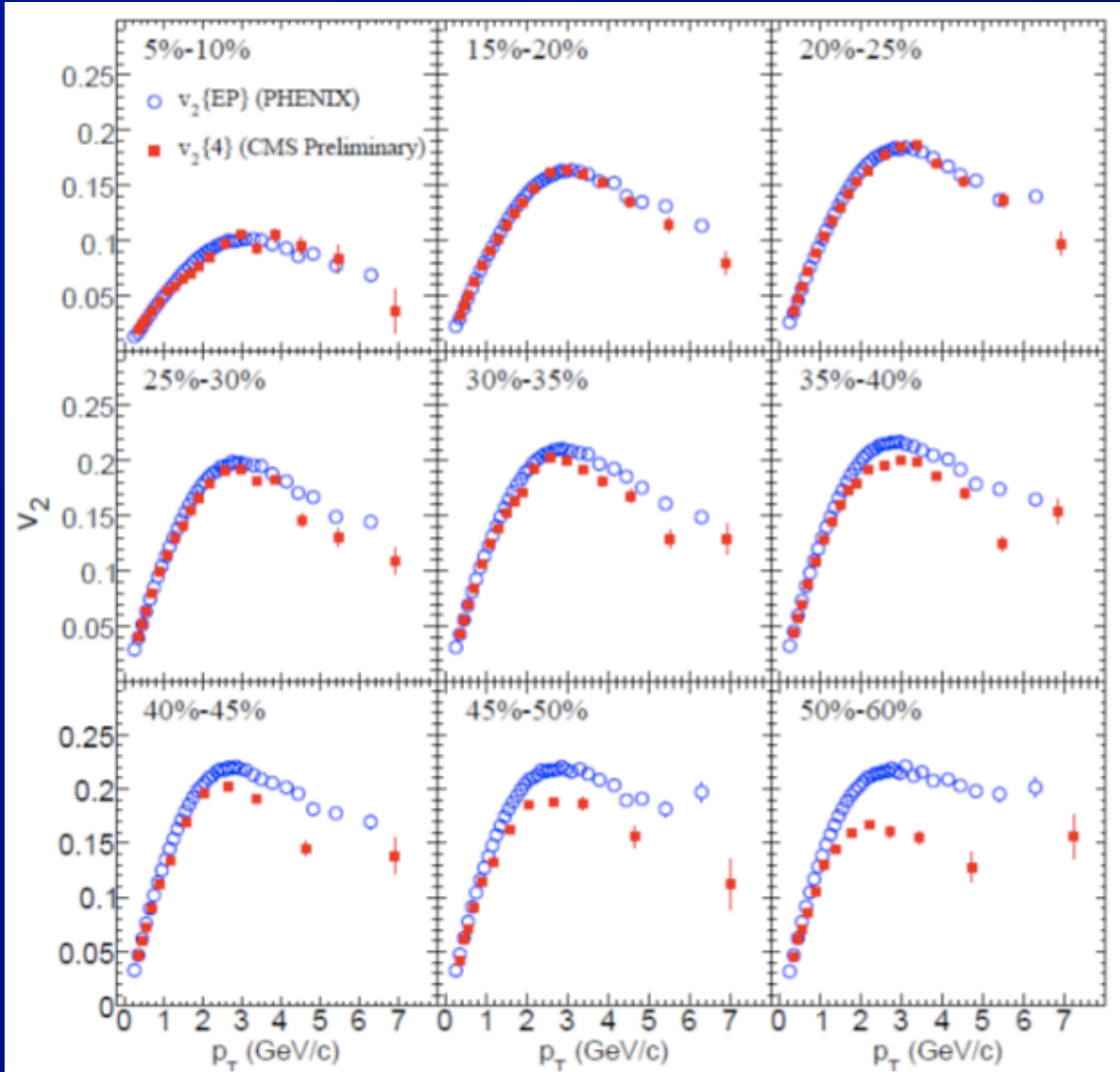




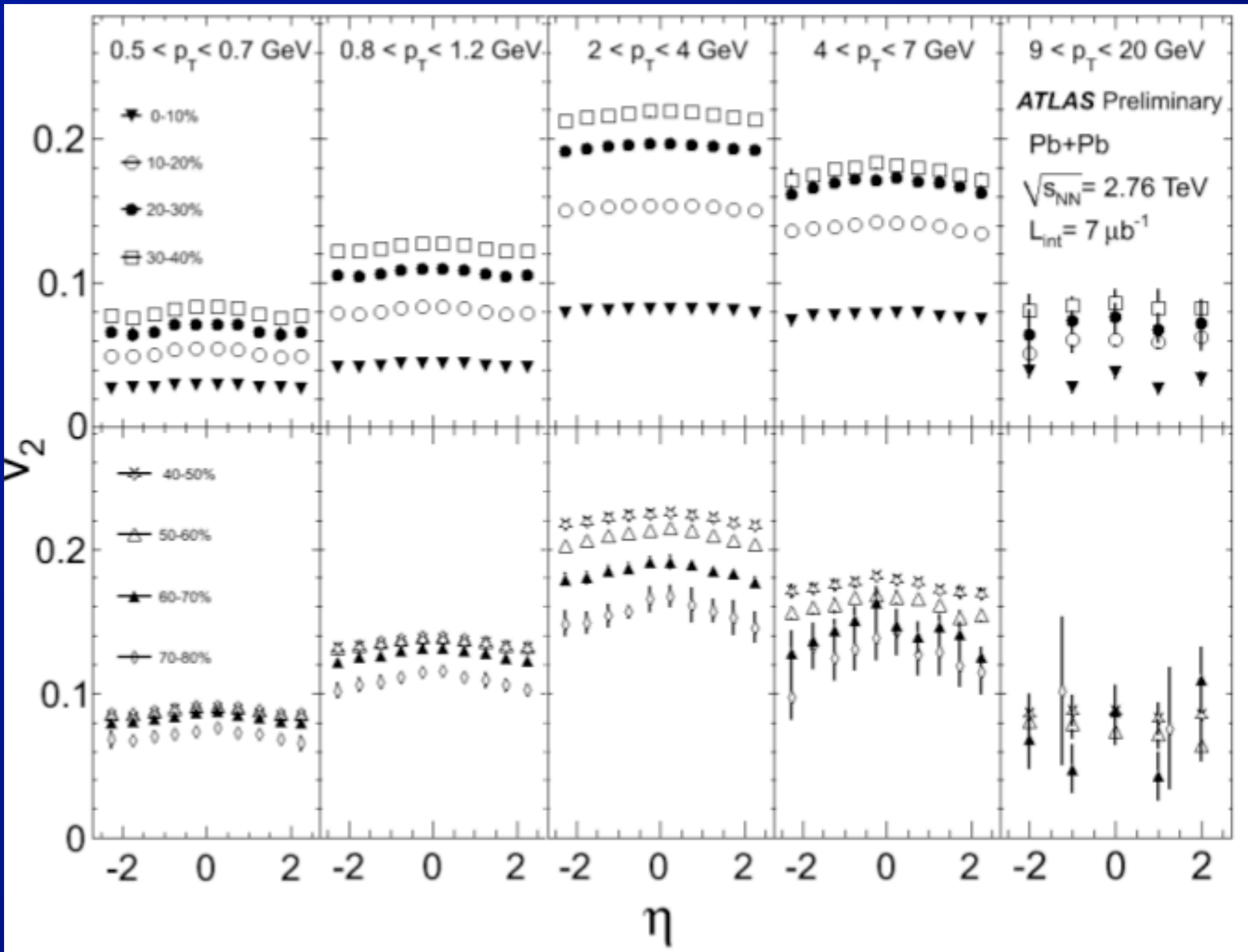
- Logarithmic variation of v_2 with $\sqrt{s}$ above 10 GeV
  - Change from RHIC to LHC is comparable to change from SPS to RHIC
    - ⇒But, beware, integral v_2 can be misleading.
    - ⇒Though it may be most directly related to η/s

Collectivity: Elliptic Flow (2)

- Identical results for $v_2(p_T)$ @ RHIC & LHC
  - Except for peripheral
    - ⇒Likely EP vs cumulant
- How?
  - Same initial eccentricity + same collectivity?
- Or
  - Accident?



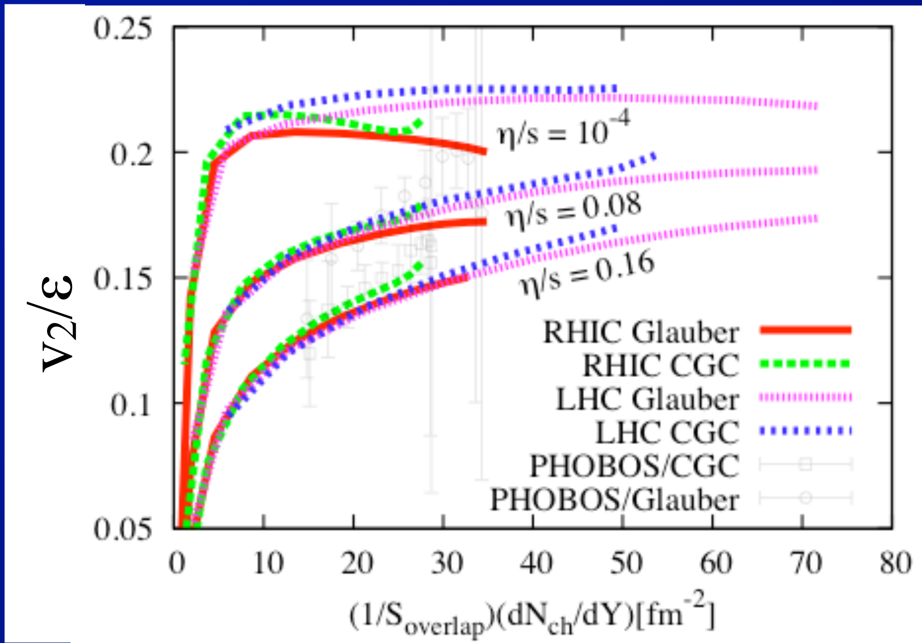
Collectivity: Elliptic Flow (3)

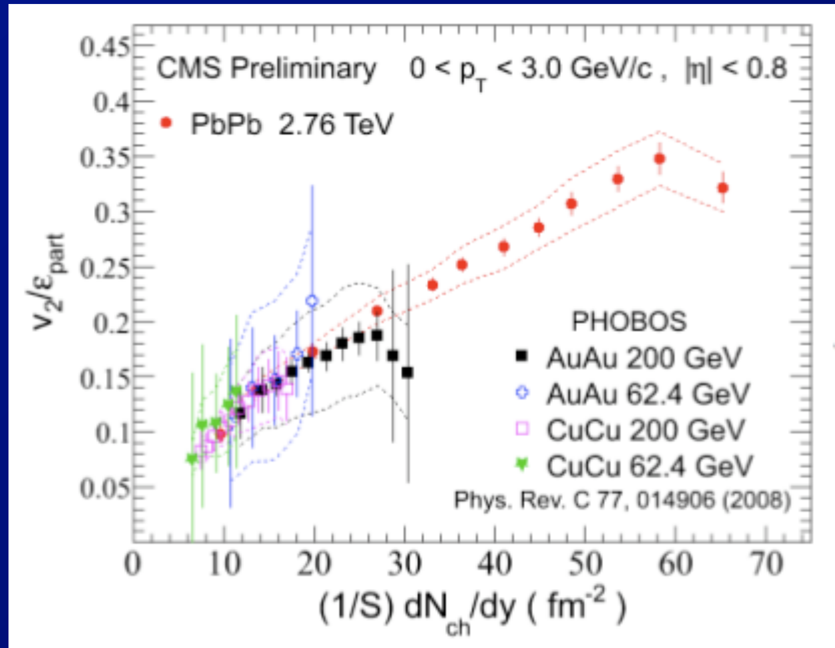


- Weak variation of v_2 with η for $p_T > 500$ MeV
  - In contrast to RHIC results.
    - ⇒Saturation of v_2 due to longer lifetime @ LHC?

Collectivity: Elliptic Flow (4)

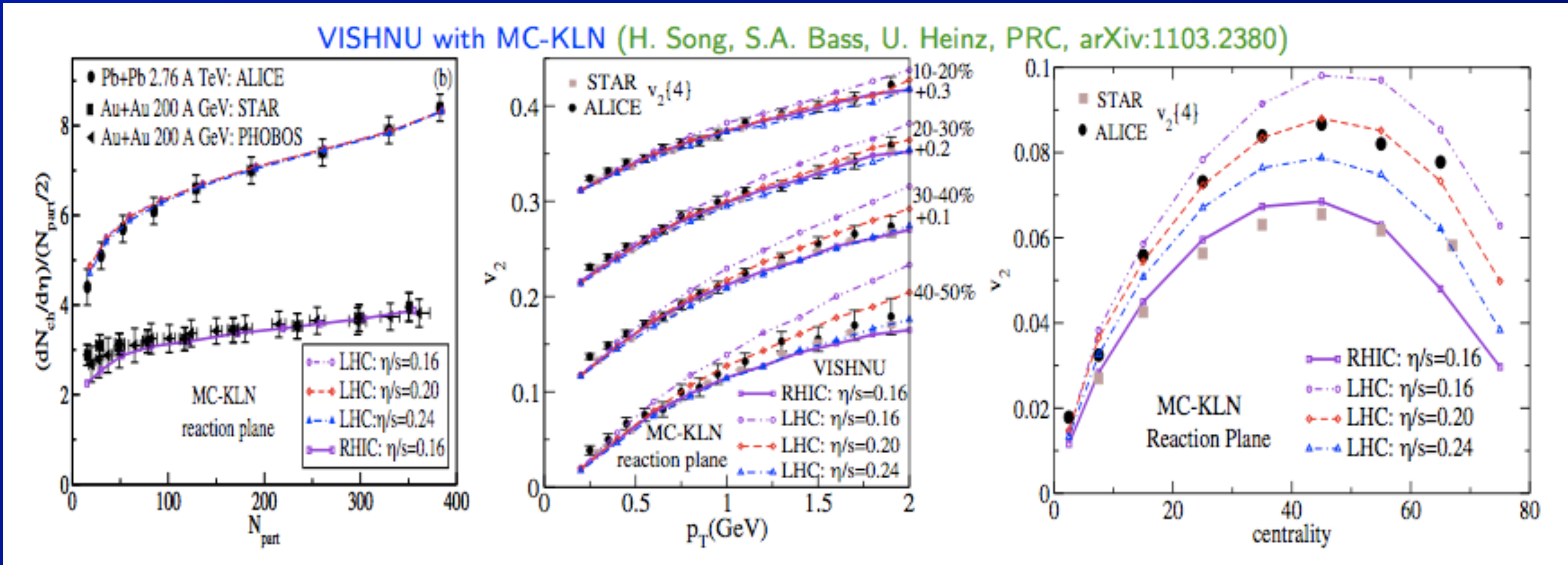
Luzum and Romatschke,
Phys. Rev. Lett. 103:262302, 2009





- **Prediction:**
  - For same η/s, little increase in v_2/ε from RHIC to LHC
    - ⇒Data show > x2 increase in v_2/ε.
- **BUT**
  - Depends on ε_{part} from Glauber -- may not be correct
  - Beware systematics on v_2 (e.g. $v_2\{2\}$ vs $v_2\{4\}$)

Collectivity: Elliptic Flow (5)

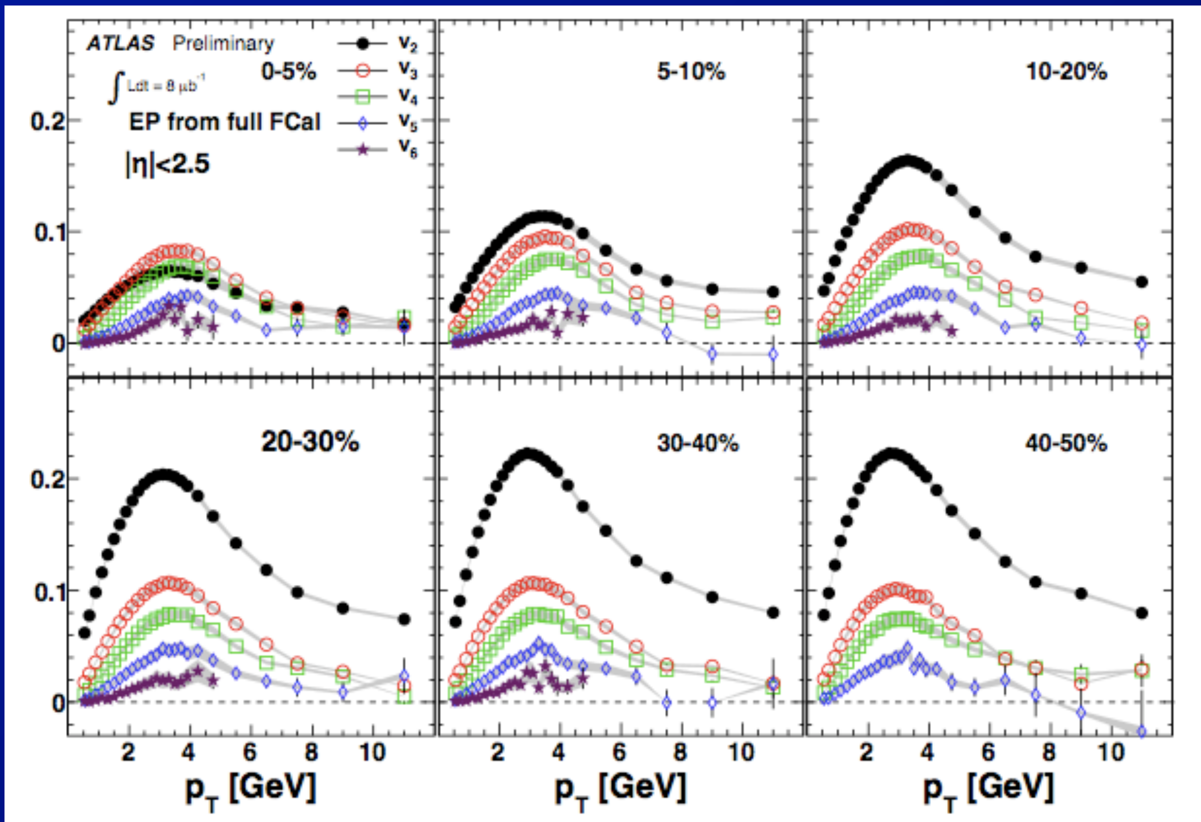


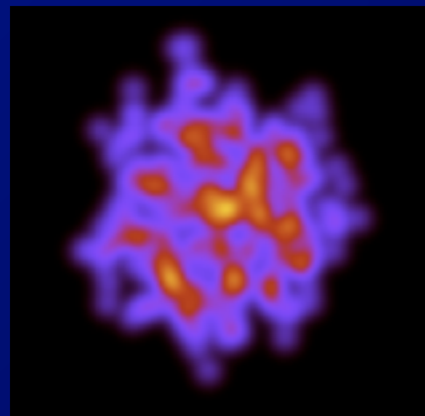
- Viscous hydro + hadronic cascade (VISHNU)
  - Compare to RHIC and LHC $dN_{chg}/d\eta$, $v_2(p_T)$, v_2(cent)
  - Using CGC initial conditions (KLN)
- Possibly higher η/s @ LHC
  - But, caveats re: initialization of $\pi^{\mu\nu}$
- Important to remember that longer lifetime of sQGP @ LHC should have consequences for v_2

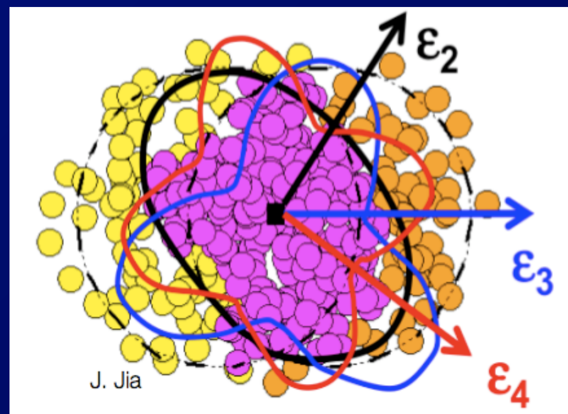
Higher Flow Harmonics

- Major paradigm shift in the field in the last year
  - Higher flow harmonics arising from initial-state fluctuations in transverse positions of participants

$$\frac{dN}{d\phi dp_T d\eta} = \frac{dN}{2\pi dp_T d\eta}\left(1 + \sum_m 2v_m \cos\left[m(\phi - \psi_m)\right]\right)$$

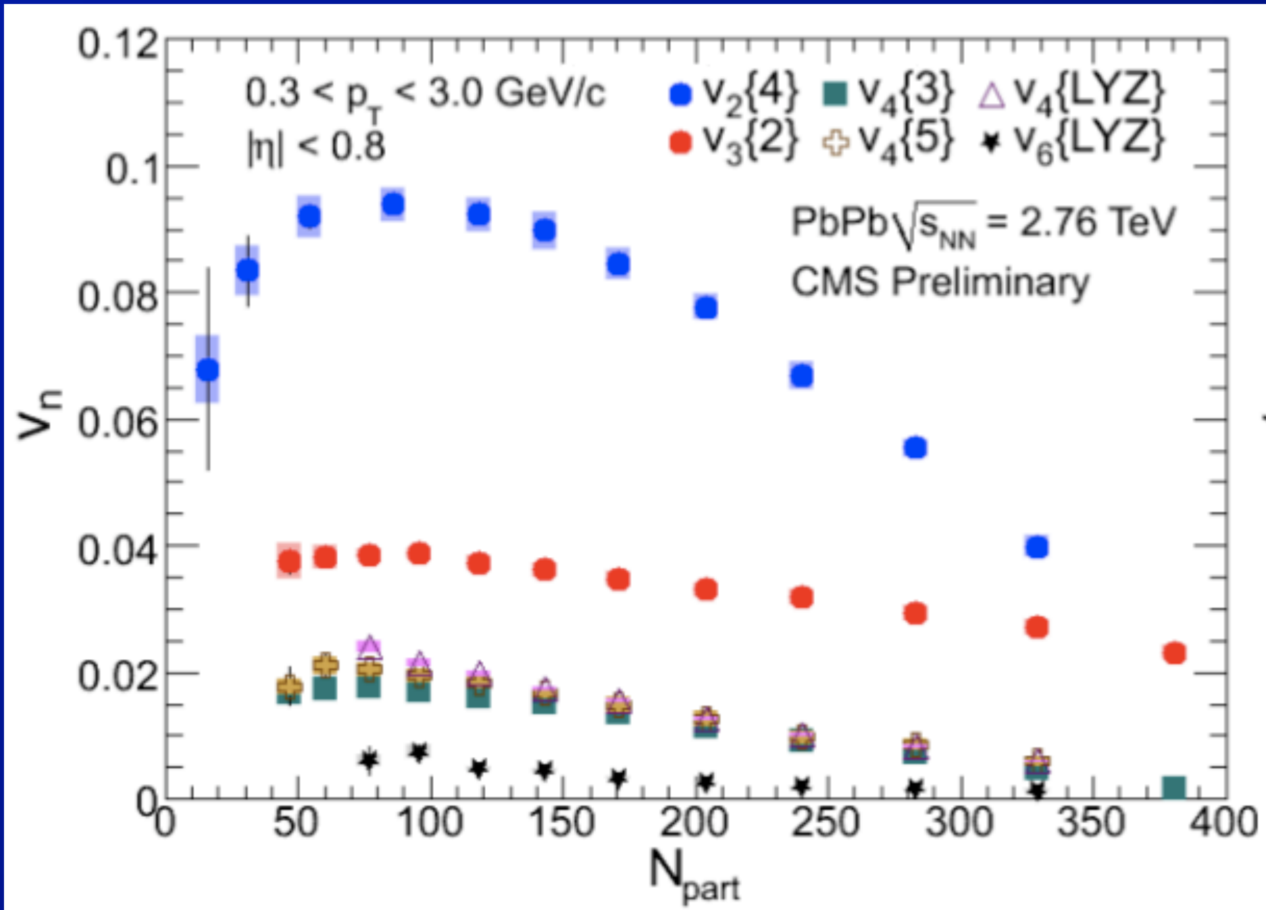


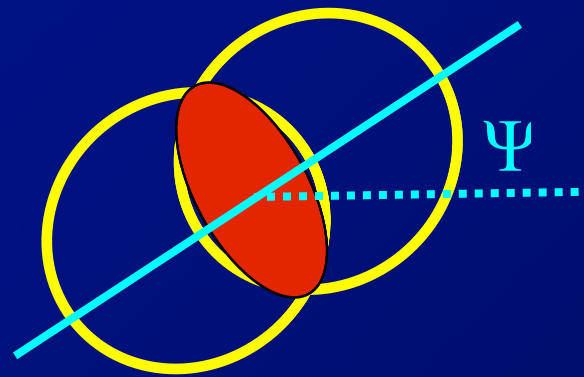


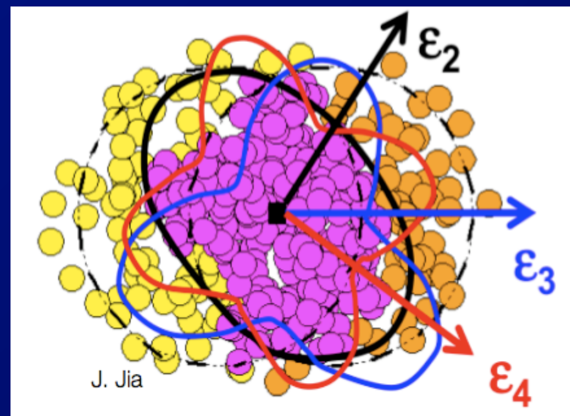


Significant results up to n = 6

Higher Flow Harmonics (2)

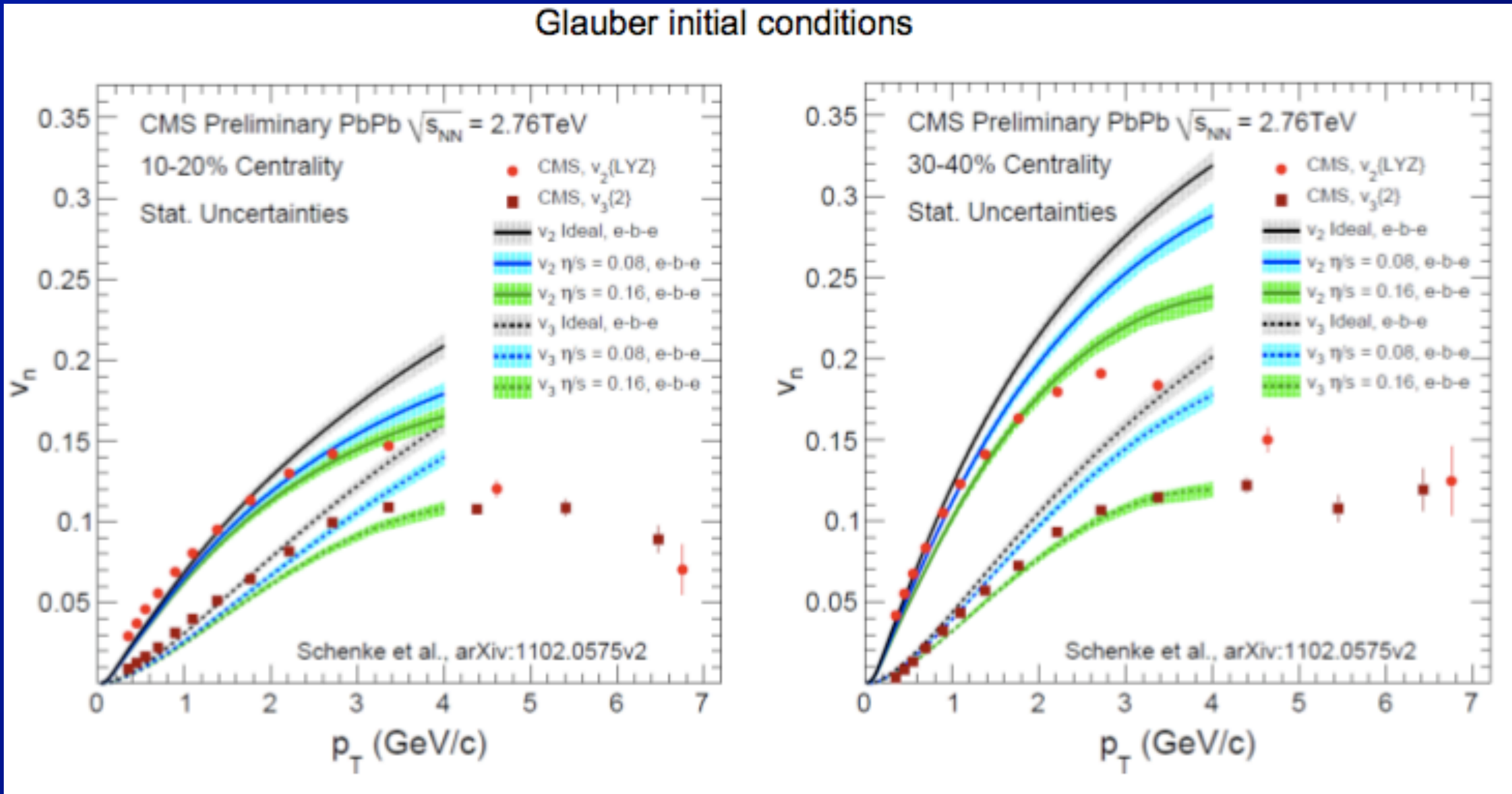






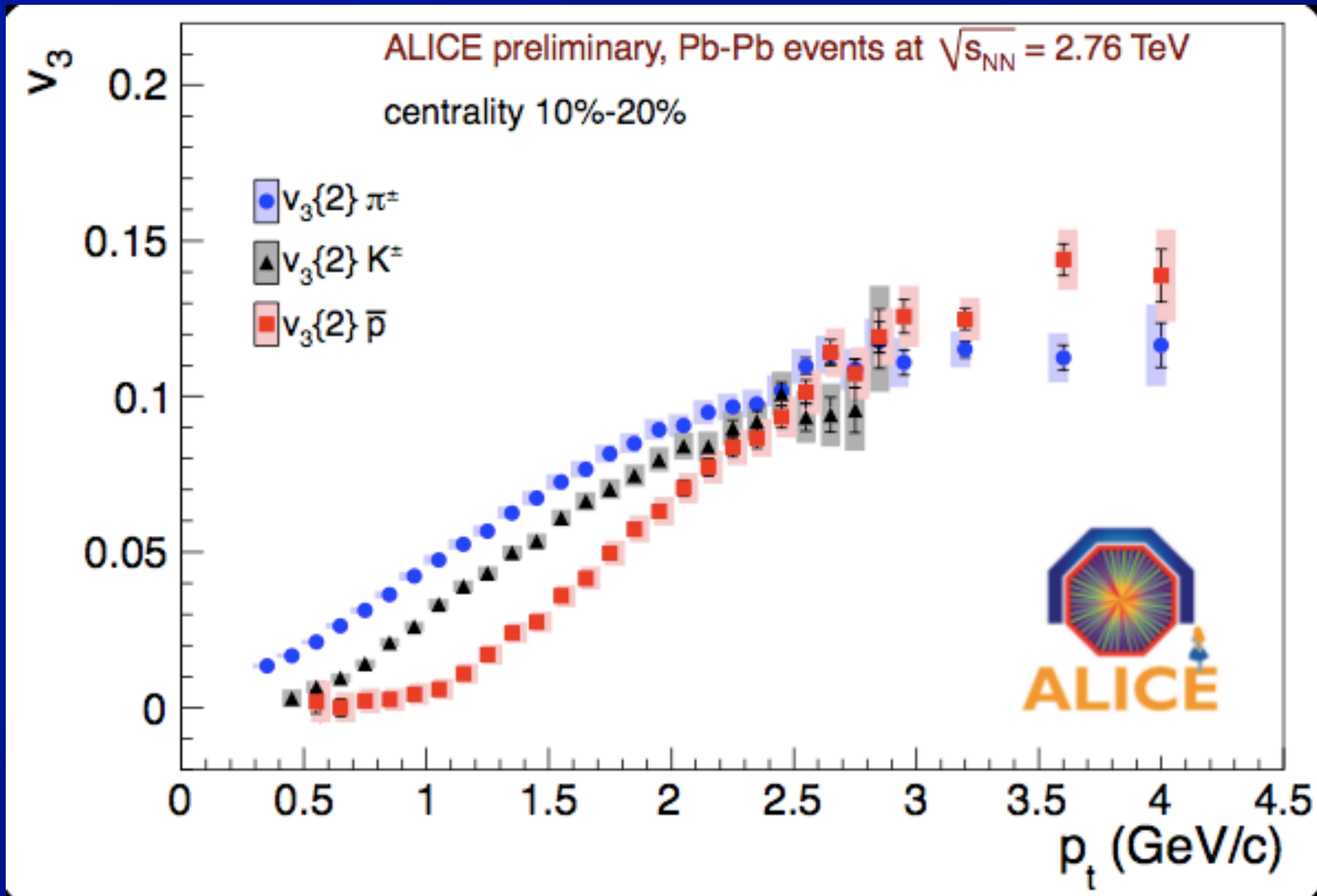
- Elliptic (v_2) flow dominates except in central collisions where $\varepsilon_2 = 0$ without fluctuations
  - v_3 has much weaker centrality dependence
    - $\Rightarrow$ consistent with participant fluctuations

Higher Flow Harmonics (3)



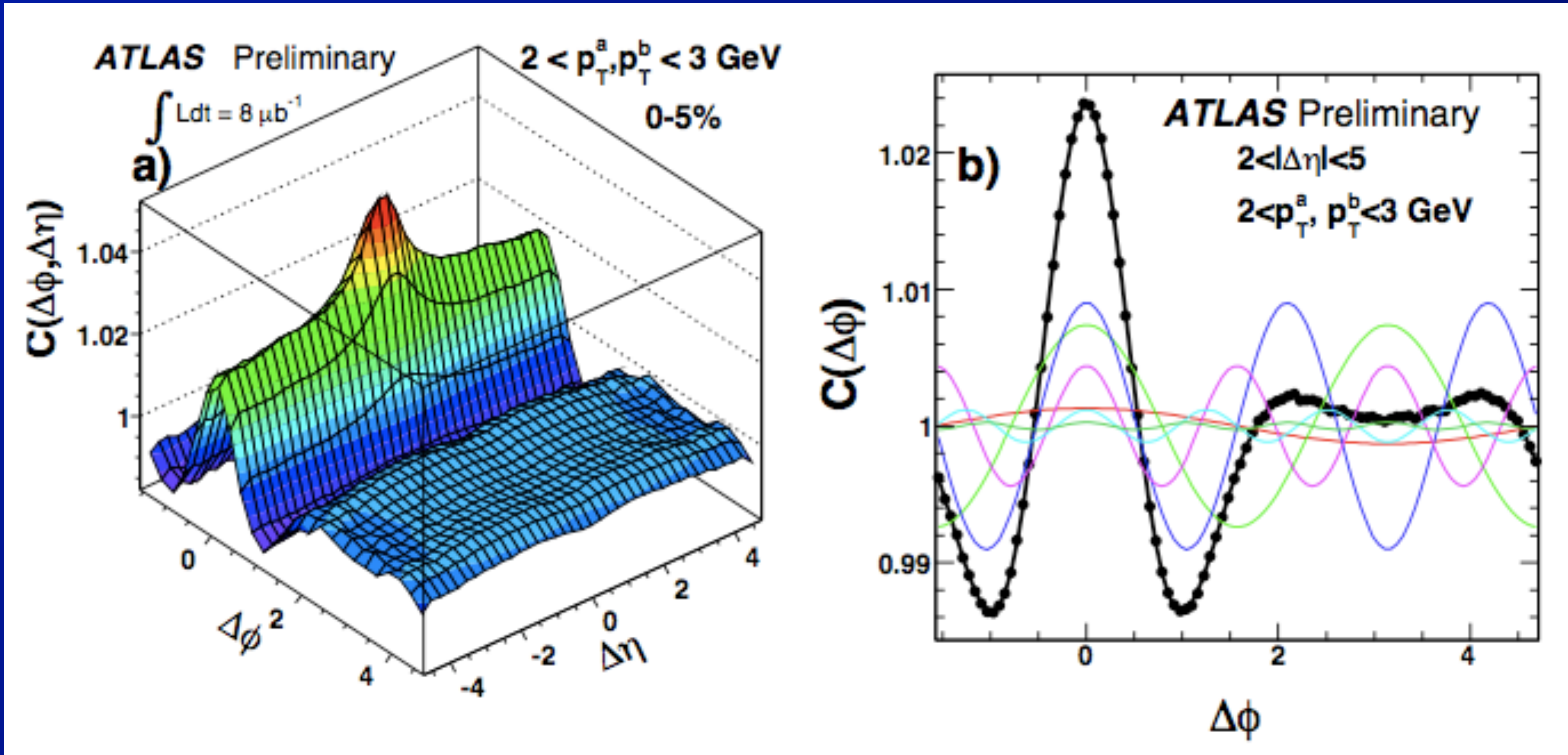
- Combination of v_2 and v_3 provide more stringent tests of hydrodynamic calculations
- Heinz *et al:*
  - ⇒Should allow resolution of Glauber vs CGC IC

Higher Flow Harmonics (4)



- Already have results for $v_3(p_T)$ for different particle species
  - Even more stringent tests of hydrodynamics
  - Including (non)contributions from hadronic cascade?

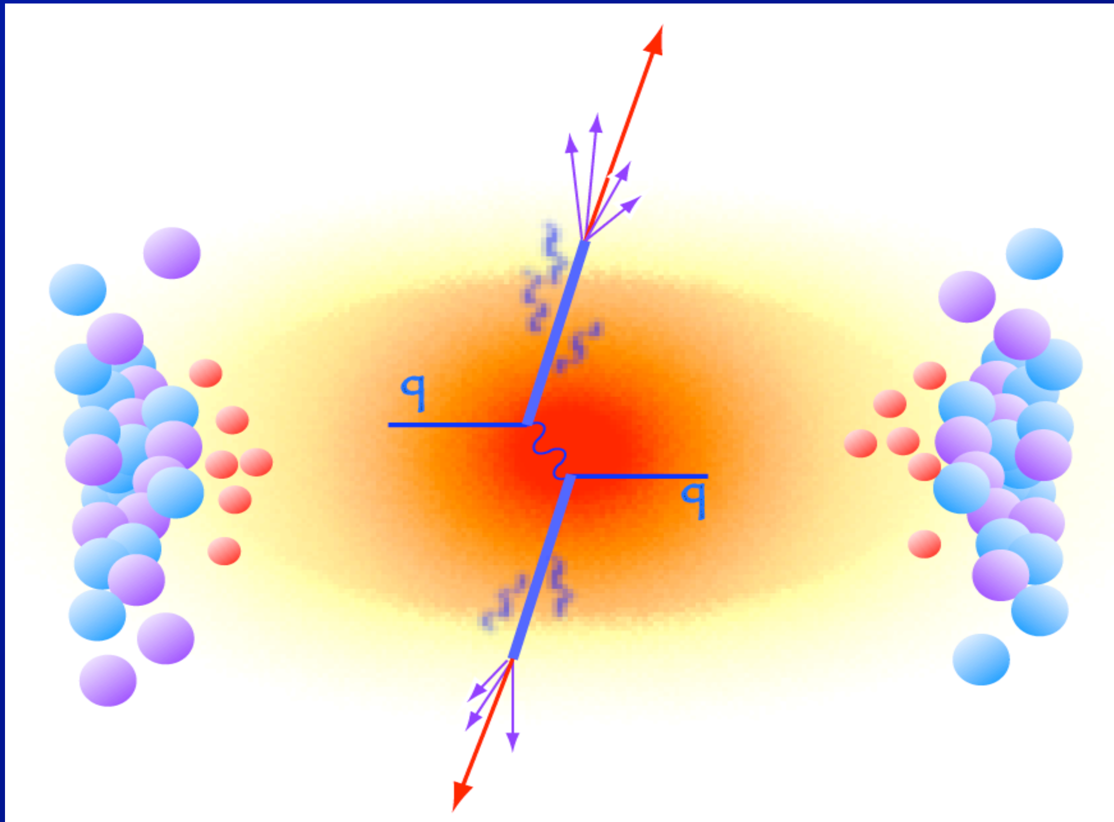
Higher Flow Harmonics (5)

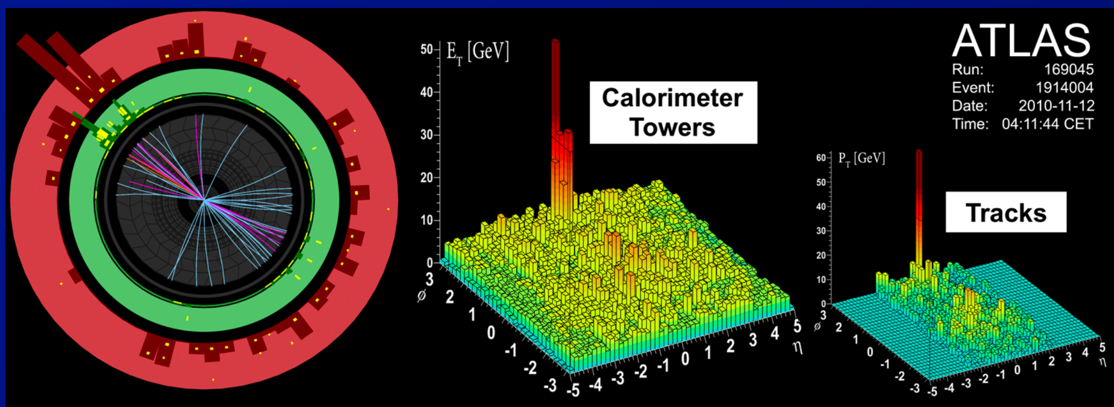


- Higher harmonics also studied using 2-particle correlations at large $\Delta\eta$
  - Sum of harmonic contributions sufficient to explain the “ridge” and the “mach(?) peaks”

    ⇒Resolves two important “problems” in the field

Jet Quenching



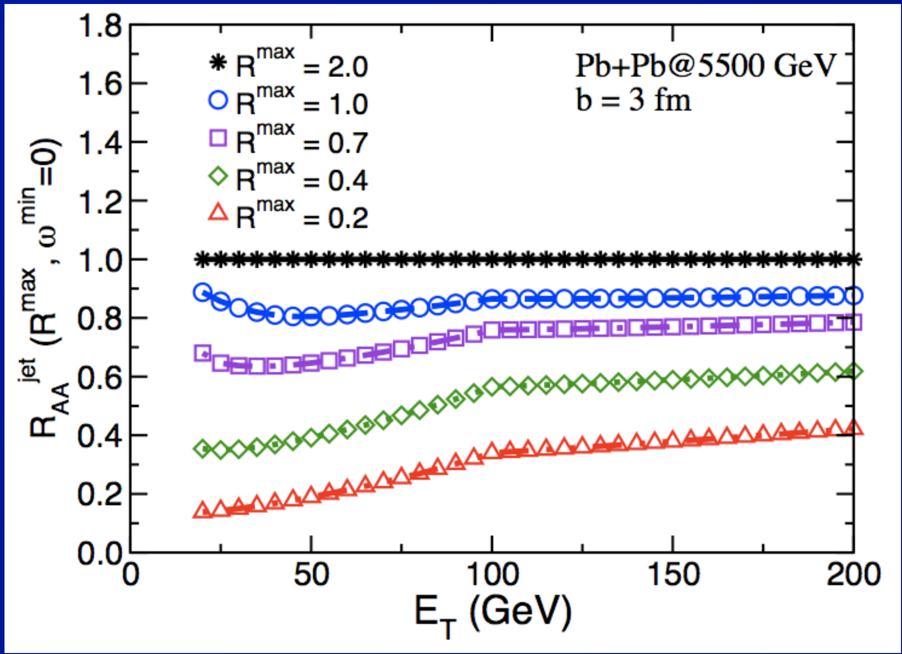


- **Key question:**
  - How do parton showers in hot medium (quark gluon plasma) differ from those in vacuum?
- **1st jet results from the LHC:**
  - Insight on differential quenching

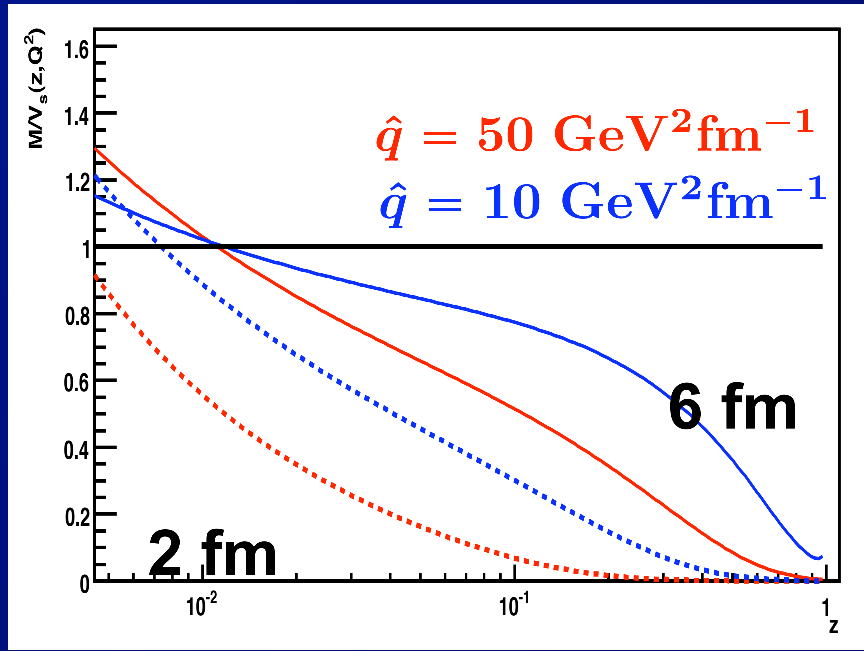
  ⇒ Next: probe “inclusive” quenching

Jet Quenching: Inclusive Observables

Vitev, Wicks, Zhang, JHEP 0811 (2008) 093



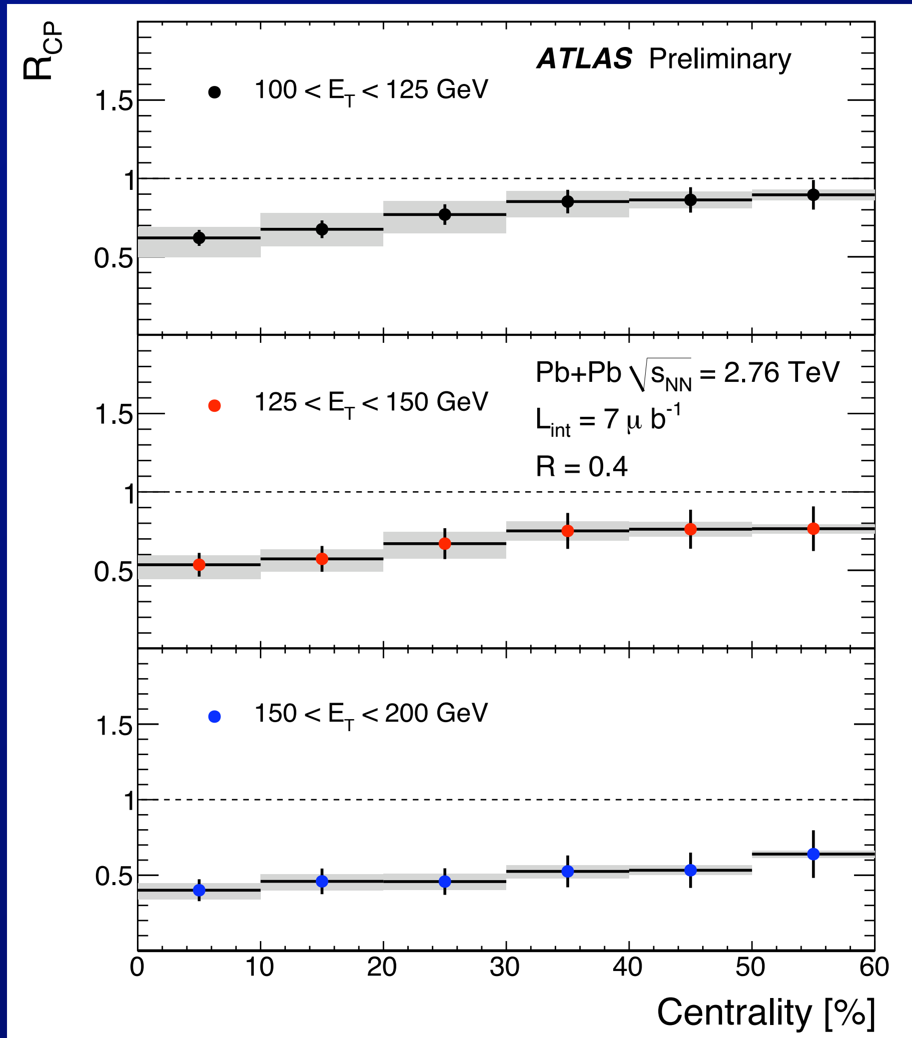
Armesto, Salgado, *et al*, JHEP 0802 (2008) 048



- Key questions:
  - ⇒(How much) Is the jet yield suppressed?
  - ⇒How does suppression depend on jet radius?
  - ⇒Is the fragmentation function D(z) modified?
  - ⇒Is the hadron angular distribution broadened?

Jet Suppression via R_{cp}

R = 0.4



Use 60-80% centrality as peripheral reference for R_{cp}

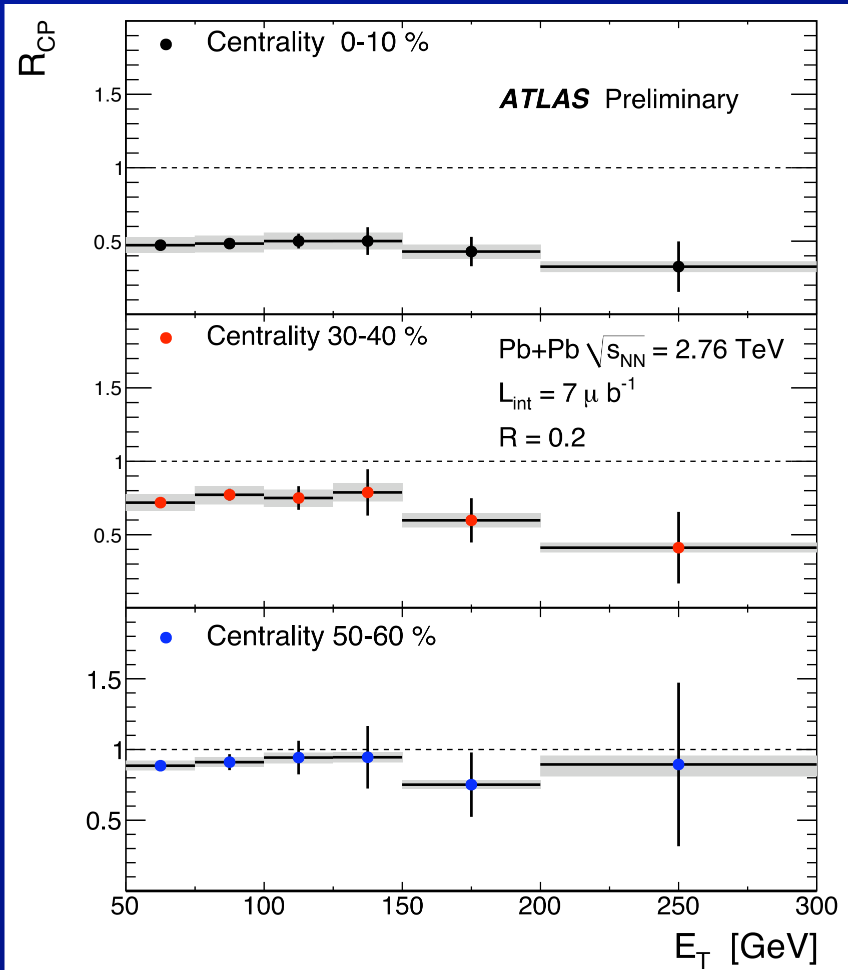
$$Rcp = \frac{\frac{1}{N_{coll}^{cent}} \frac{1}{N_{evt}^{cent}} \frac{dN_{jet}^{cent}}{dE_T}}{\frac{1}{N_{coll}^{60-80}} \frac{1}{N_{evt}^{60-80}} \frac{dN_{jet}^{60-80}}{dE_T}}$$

- **Observe:**

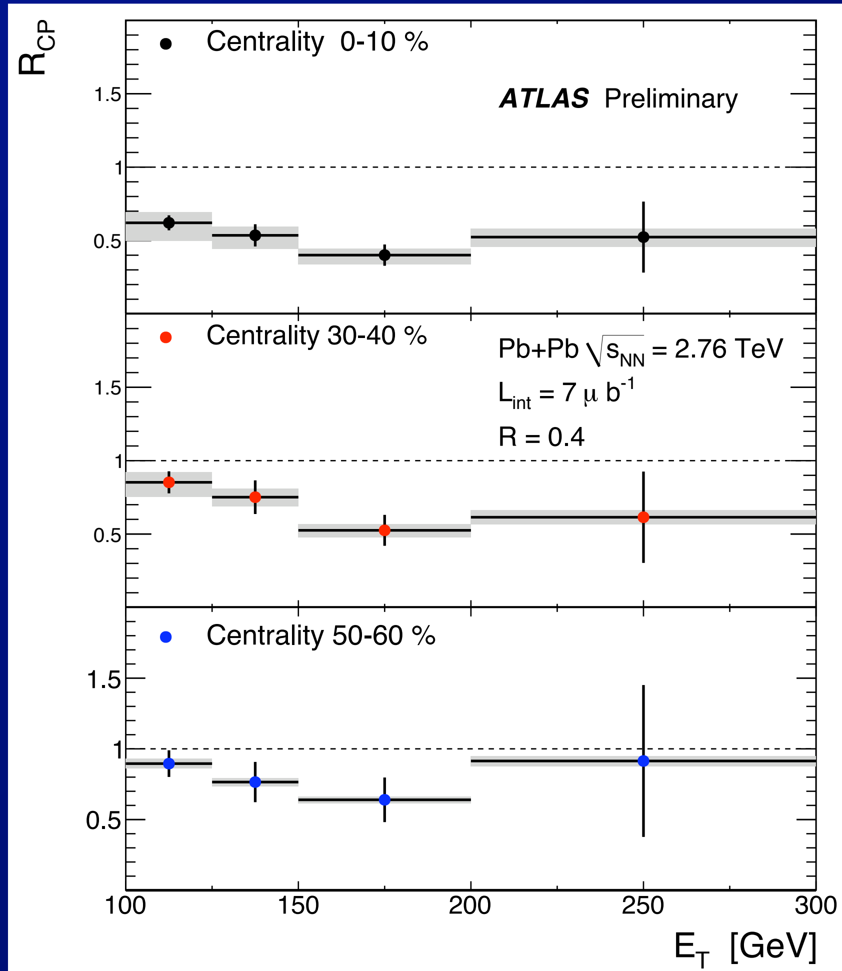
⇒Factor of ≈ 2 suppression of jet yield/N_{coll} in central (0-10%) collisions relative to 60-80% collisions.

Jet Suppression via R_{cp} (2)

R = 0.2

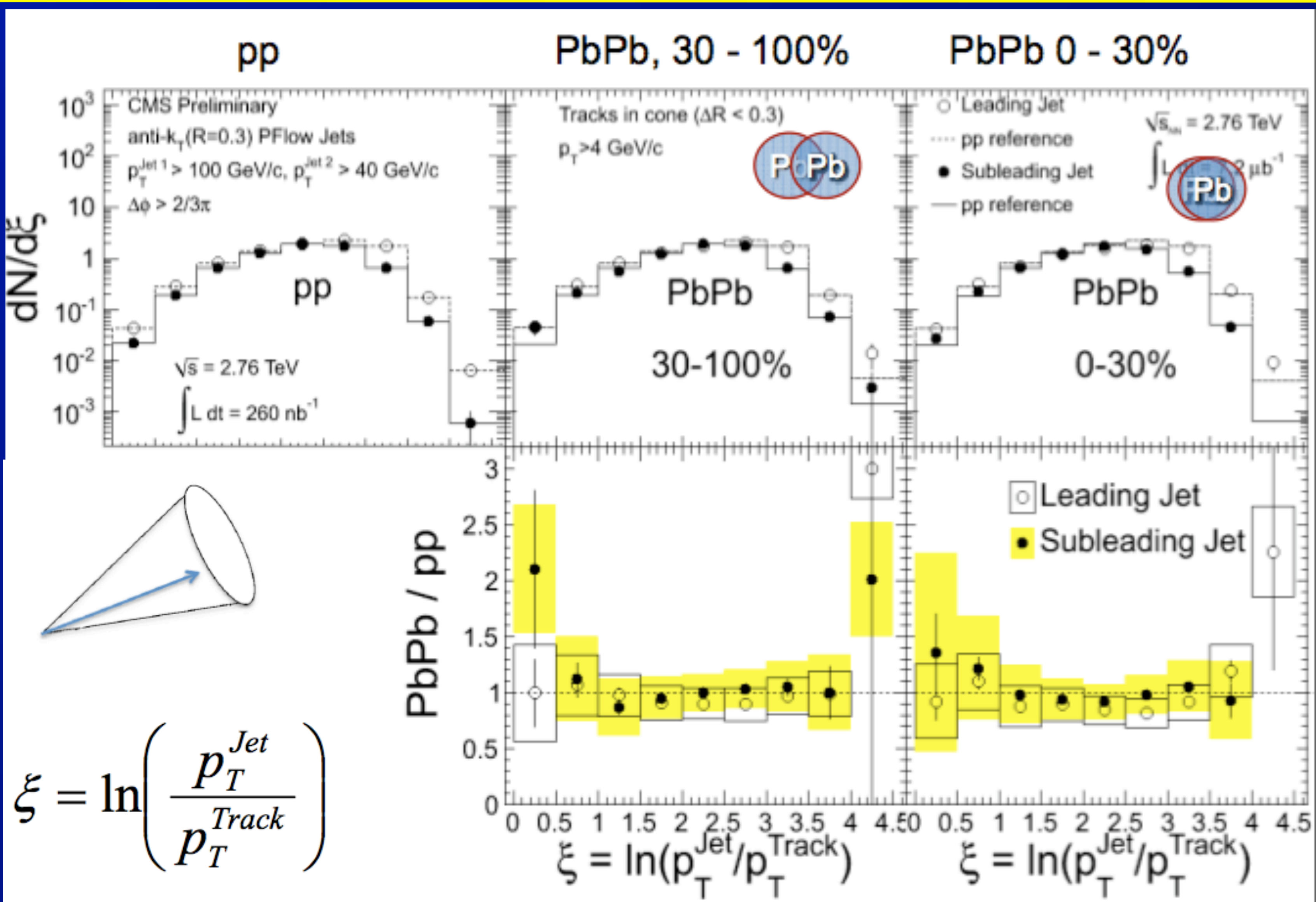


R = 0.4



- **Observe**
  - ⇒ Suppression E_T independent within errors
  - ⇒ Same for R = 0.2 and R = 0.4 within errors

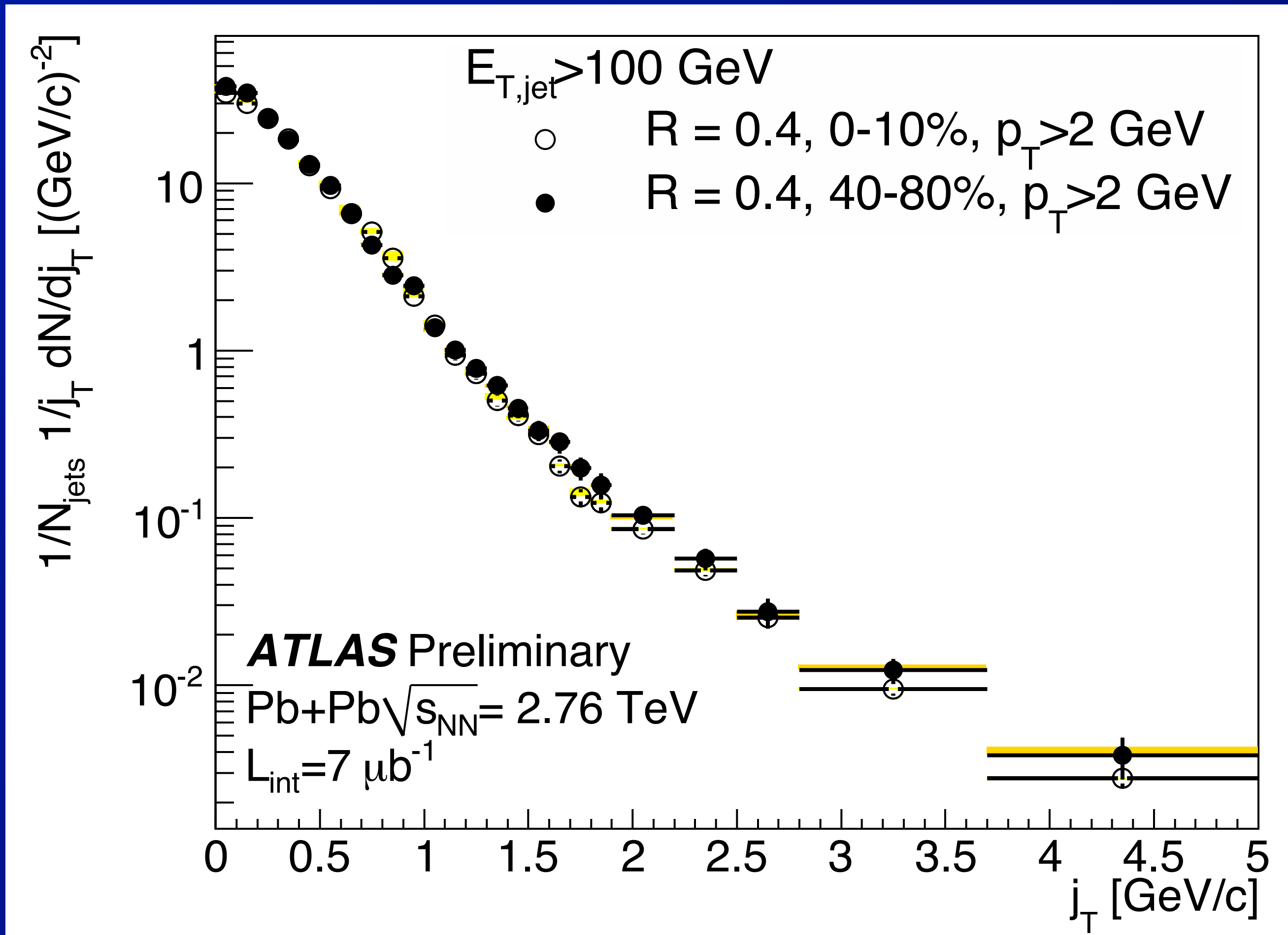
Jet Fragmentation

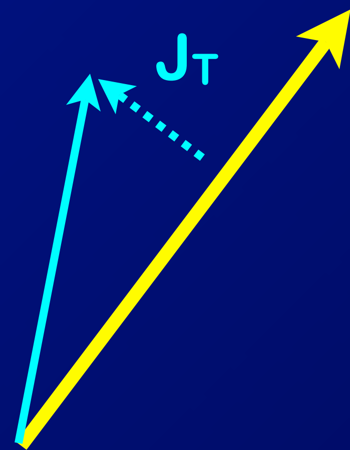


$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$

- No apparent modifications of (longitudinal) jet fragmentation function.

Jet Fragmentation (Transverse)

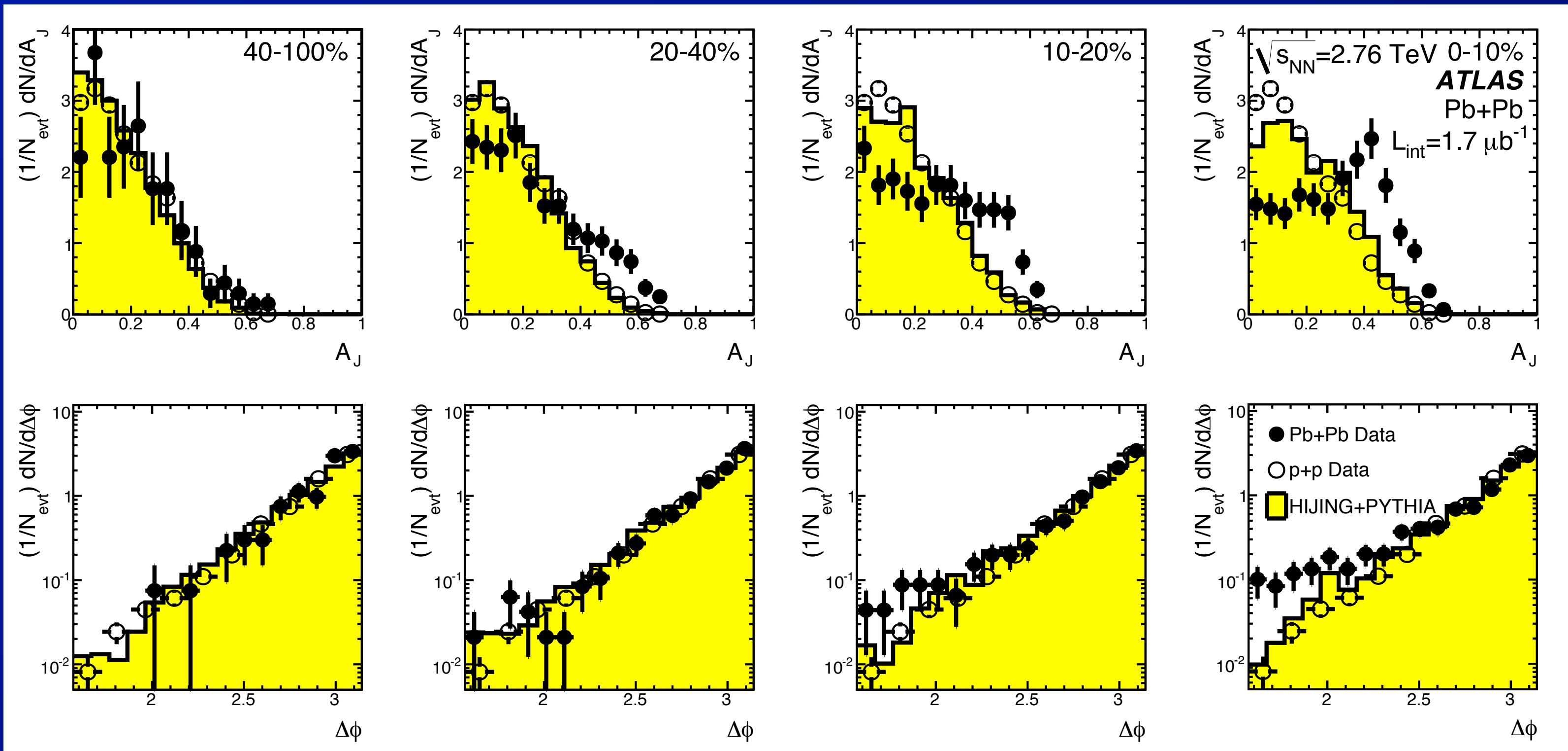




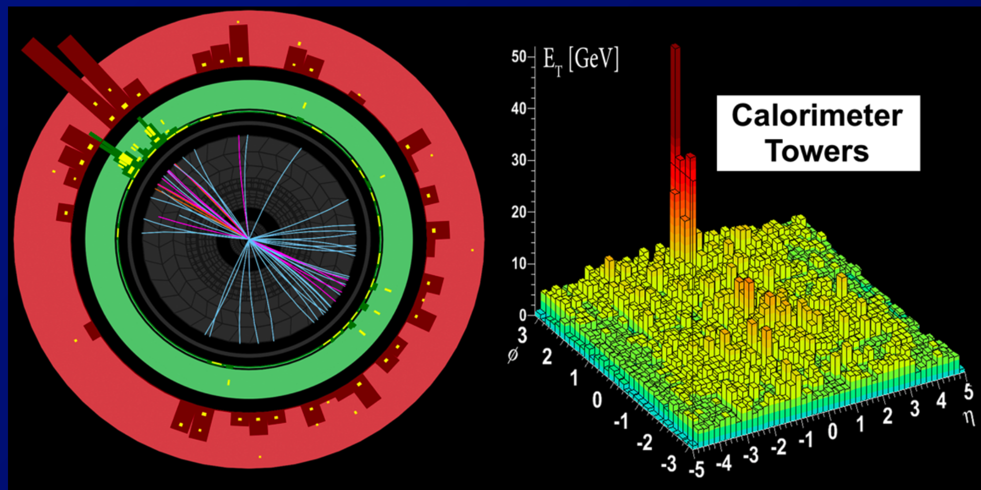
- Measure distribution of fragment p_T normal to jet axis: $j_T \equiv p_T^{\rm had} \sin\Delta R = p_T^{\rm had}\sin\left(\sqrt{\Delta\eta^2+\Delta\phi^2}\right)$
  - Compare central (0-10%) to peripheral (60-80%)

    ⇒No substantial broadening observed.

Di-jet asymmetry - ATLAS PRL

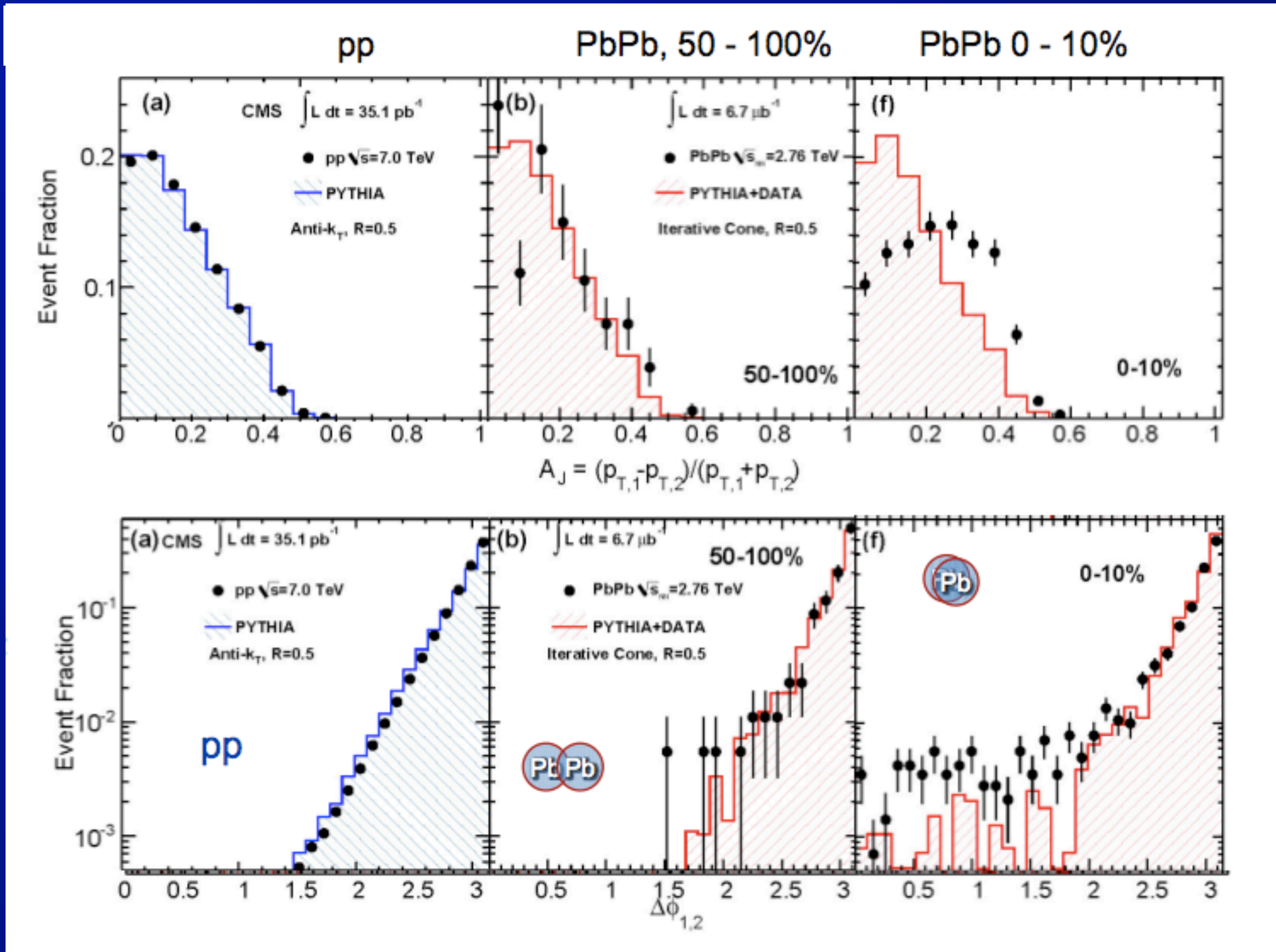


$$A_J \equiv \frac{E_{T1} - E_{T2}}{E_{T2} + E_{T1}}$$



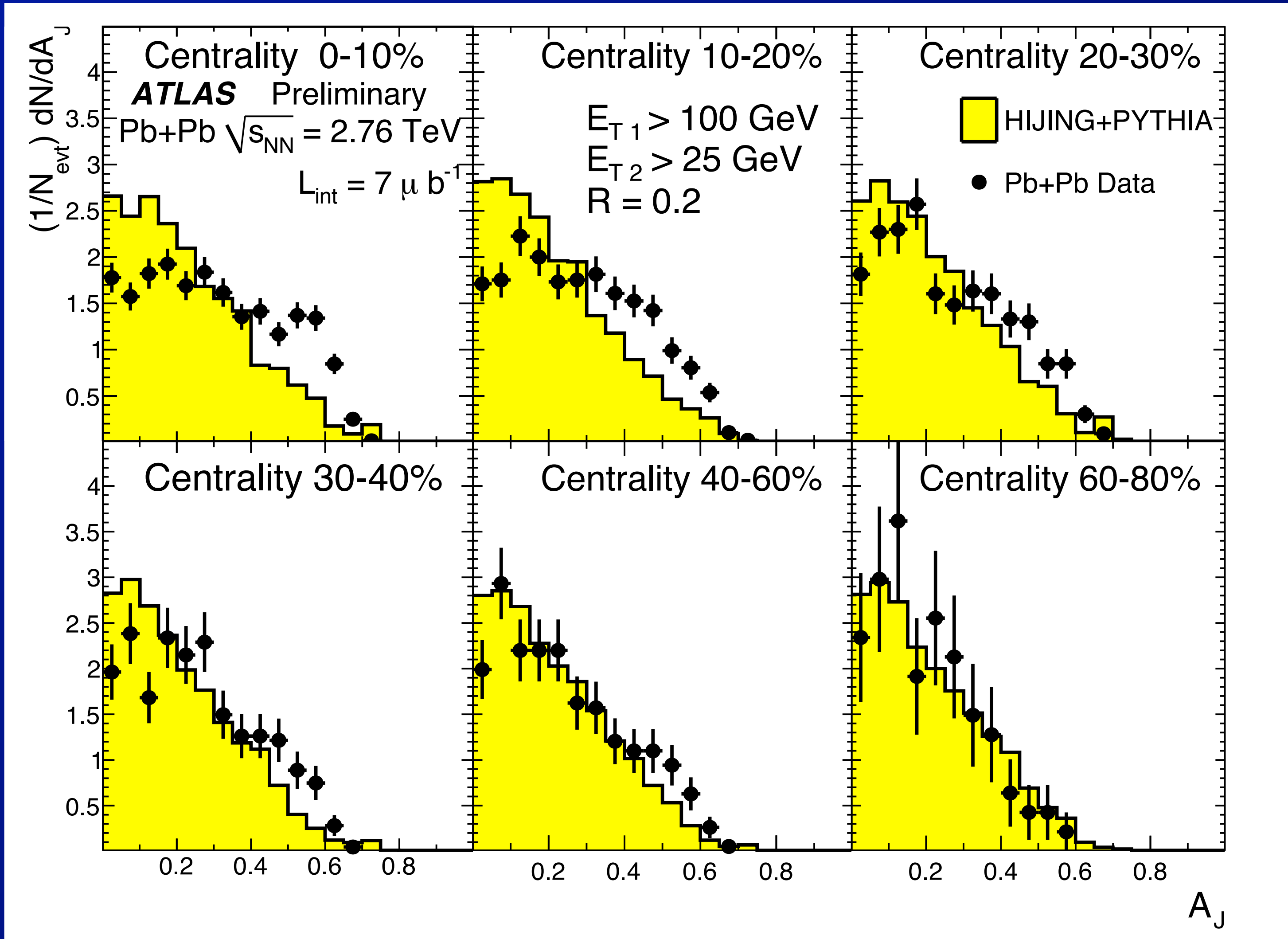
- “Holy grail” of jet quenching
  - But, due to quenching or underlying event?

Di-jet asymmetry (2)



- Similar results from CMS with very different experimental systematics

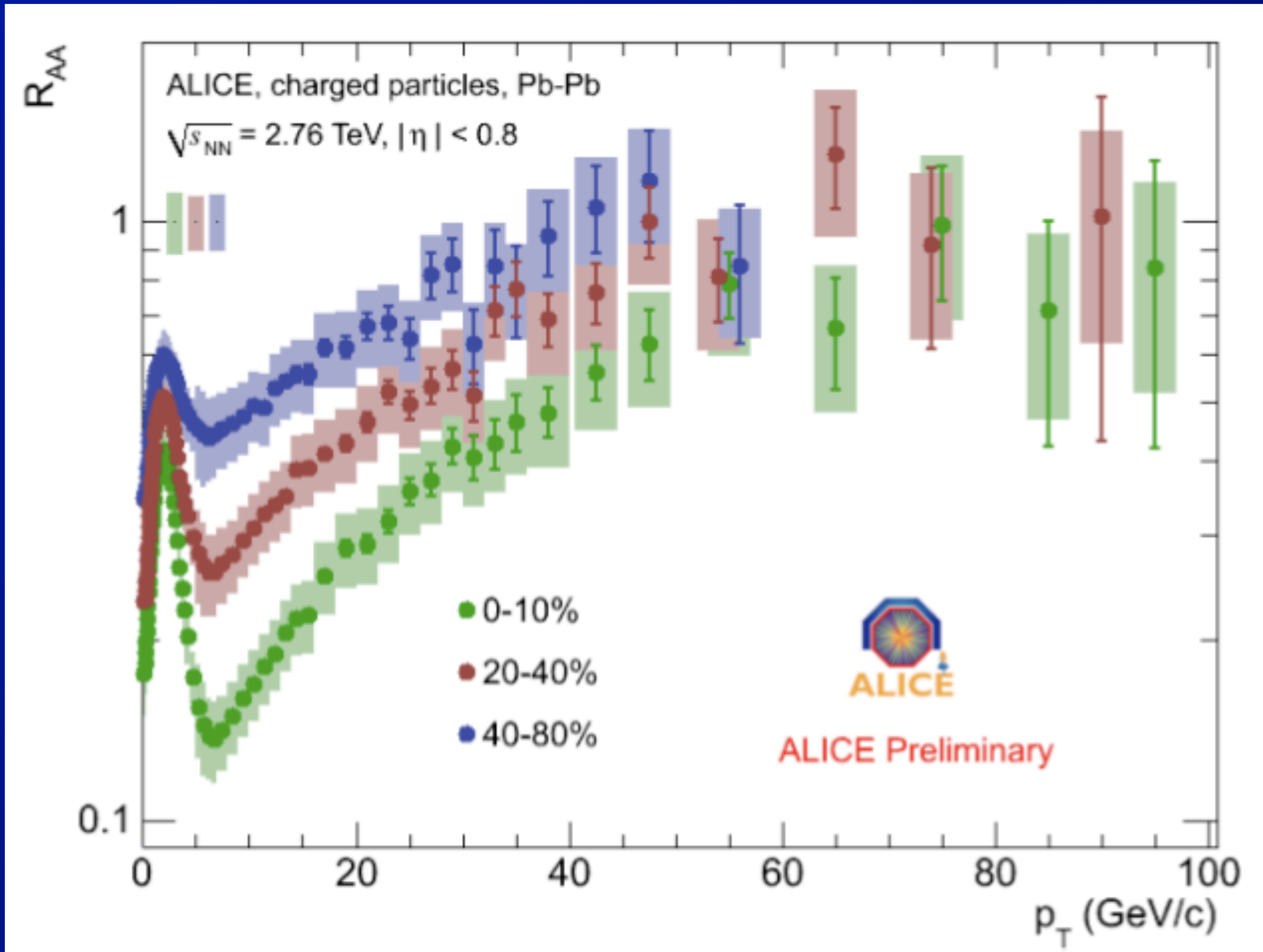
Di-jet Asymmetry, R = 0.2



- Strong modification of di-jet asymmetry in R = 0.2 jets (1/4 area of R = 0.4)

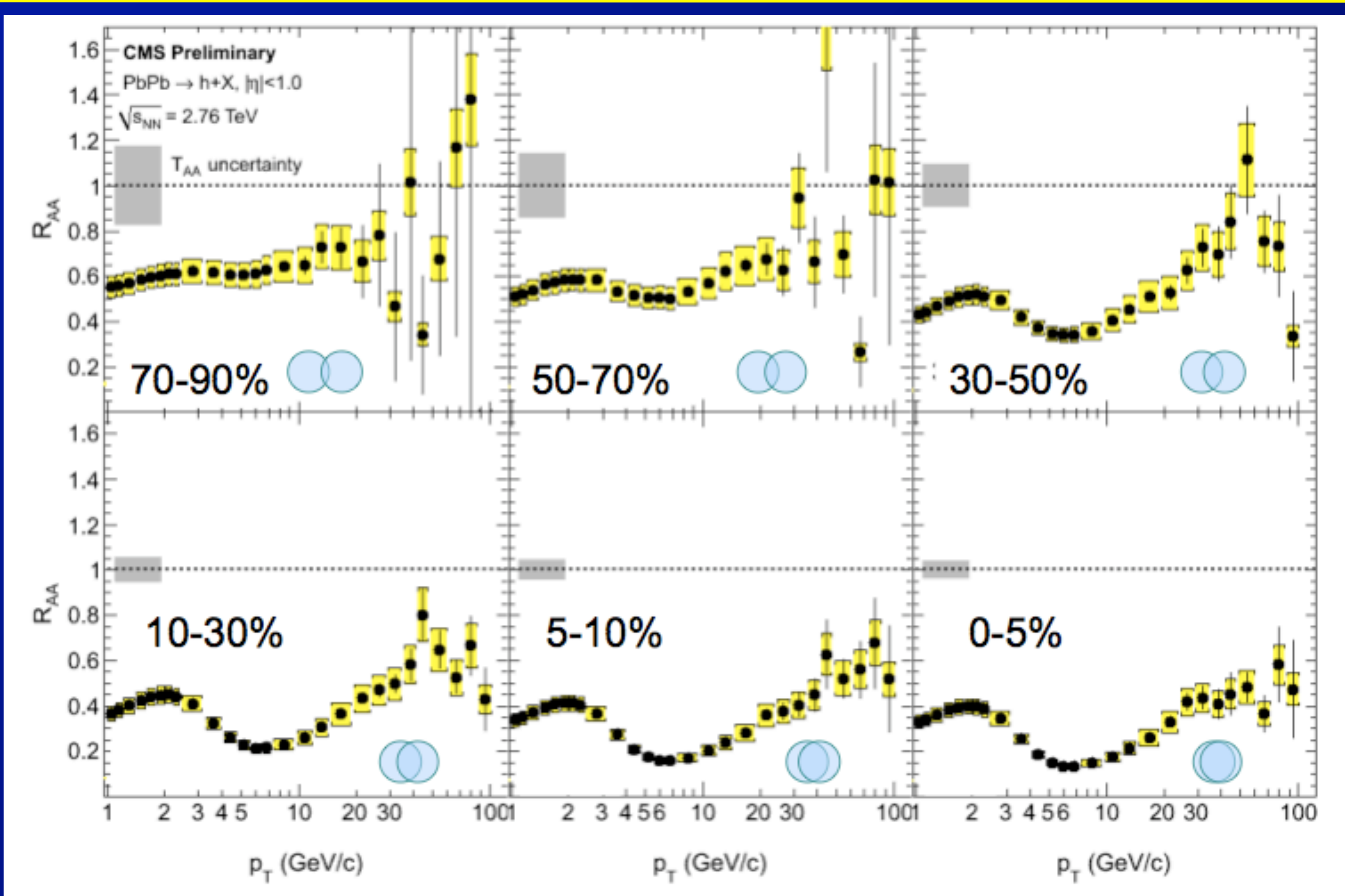
  ⇒ Asymmetry not due to underlying event

Charged Particle Suppression



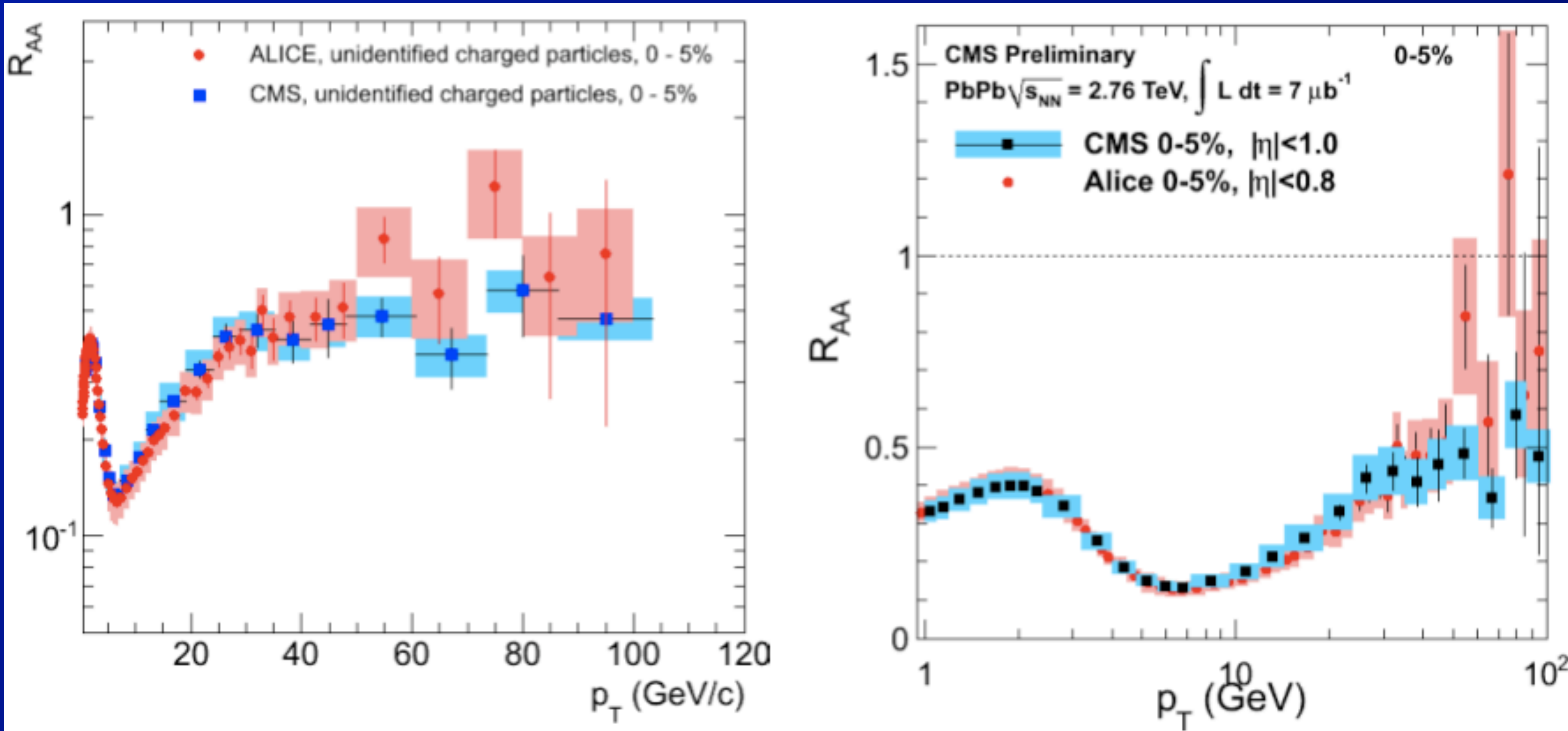
- **Strong variation of R_{AA} with p_T**
  - Long sought indications of radiative energy loss?

Charged Particle Suppression (2)



- CMS (and ATLAS) obtain similar results
  - ⇒R_{AA} ~ 0.4 at high p_T in central collisions

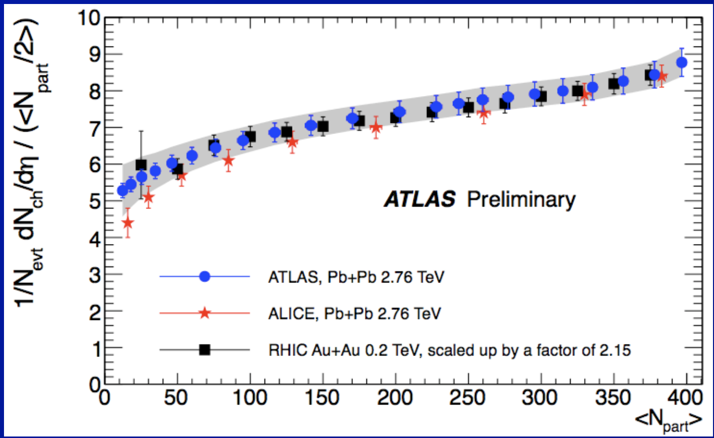
Charged Particle Suppression (3)

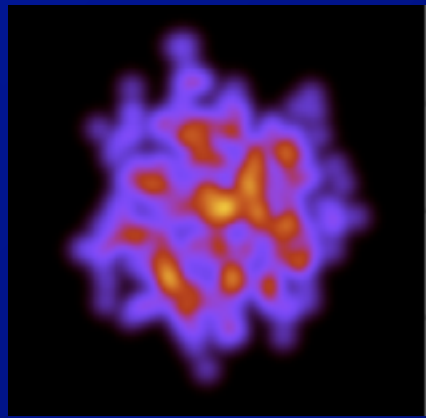


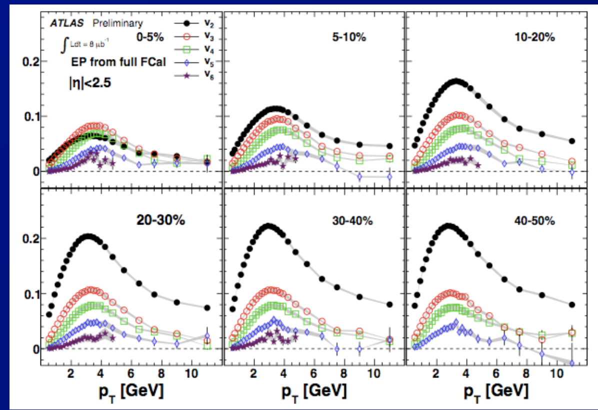
- CMS and ALICE results consistent at high p_T
  - But, both require extrapolation of p-p in $\sqrt{s}$ or p_T
- CMS result naively compatible with ATLAS jet suppression (0.5, flat in E_T).

⇒Does physics change for p_T > 30-40 GeV?

Summary & Comments/Questions

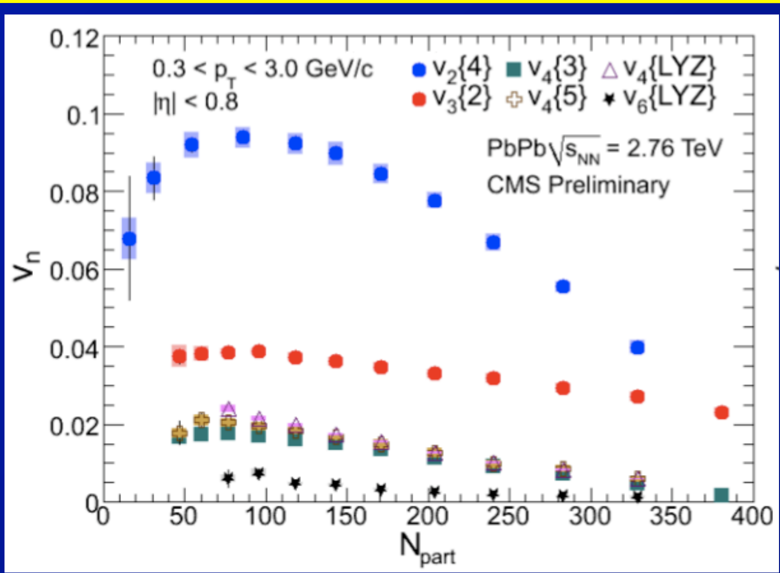


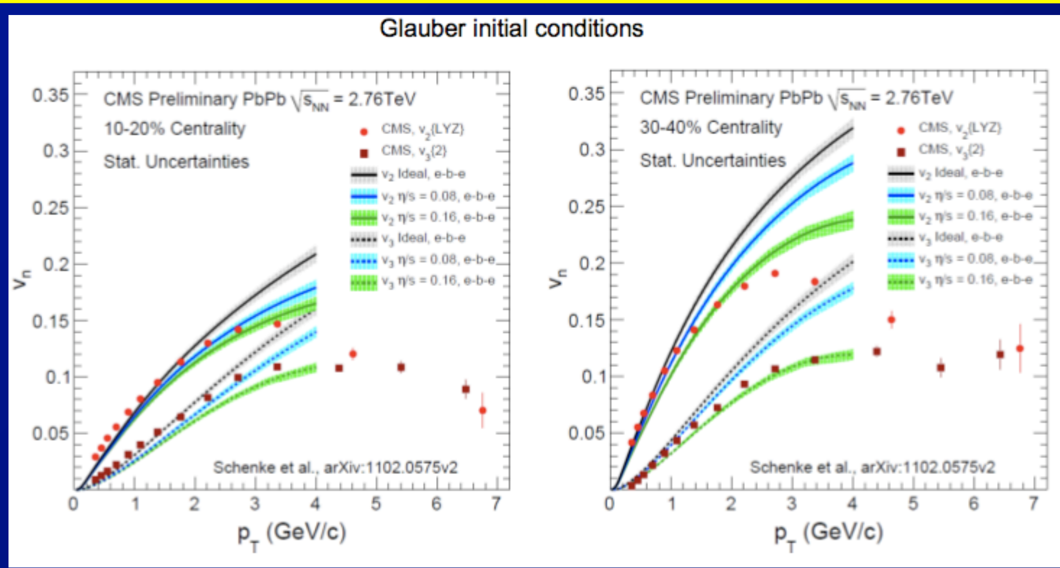




- LHC multiplicity (and E_T) results provide key data on LHC initial conditions
  - ⇒But insight on the physics?
- Physics of bulk particle production also determines initial state geometry & fluctuations
  - ⇒Possibility for v_n to constrain theoretical descriptions of the initial conditions
  - ⇒But, do we have the correct physical picture?
- Will RHIC d+Au, LHC p+Pb be sufficient?
  - ⇒ My opinion: new ideas and /or e+A needed.

Summary & Comments/Questions (2)

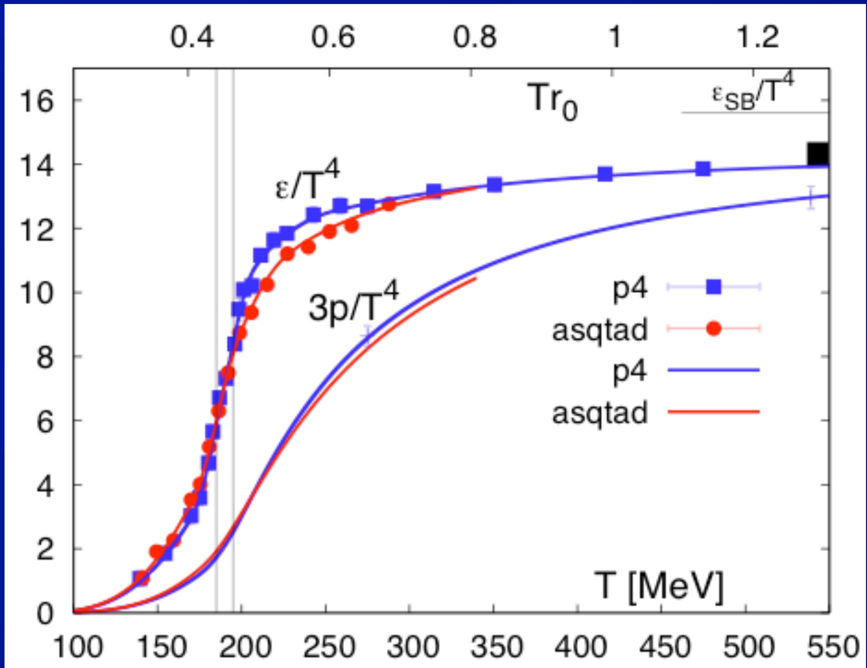


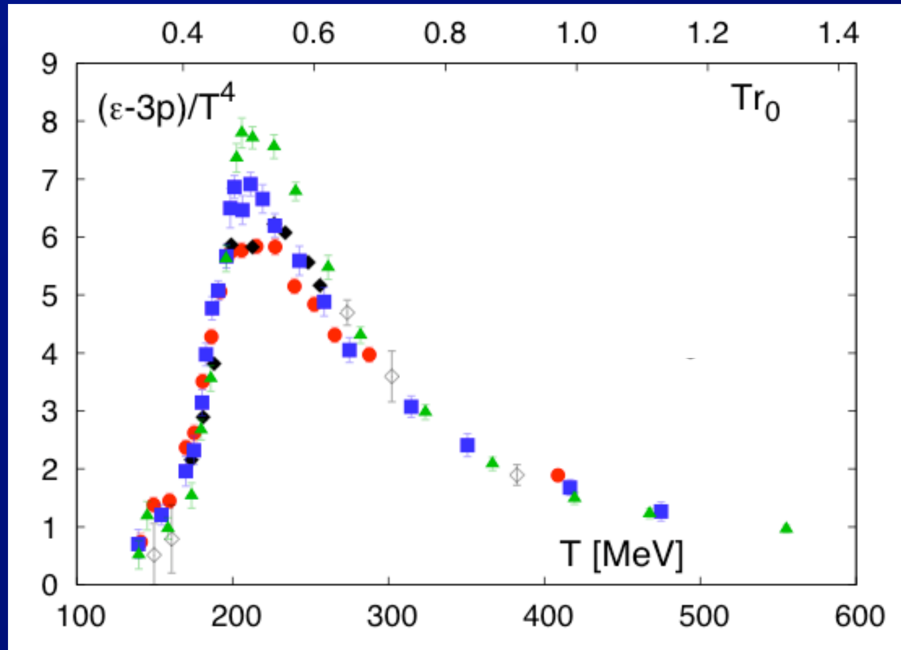


- **Collective flow physics qualitatively similar at RHIC and the LHC**
  - But, longer lifetime of sQGP at LHC results in less sensitivity to hadronic stage.
- **For both RHIC, LHC v_n physics will revolutionize study of collective flow**
  - ⇒Precision determination of transport coefficients?
  - ⇒Subject to initial condition uncertainties.

Summary & Comments/Questions (3)

Energy Density or pressure



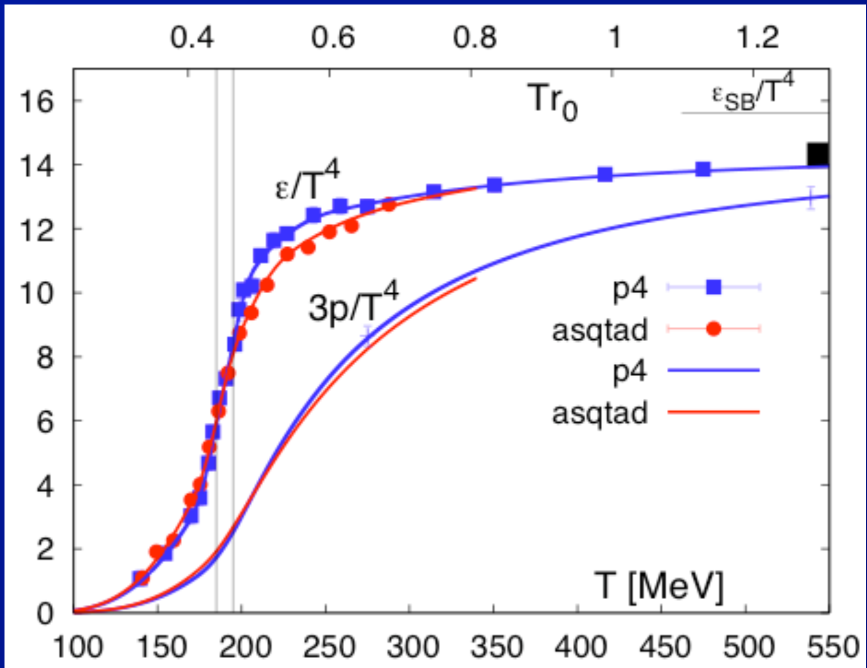


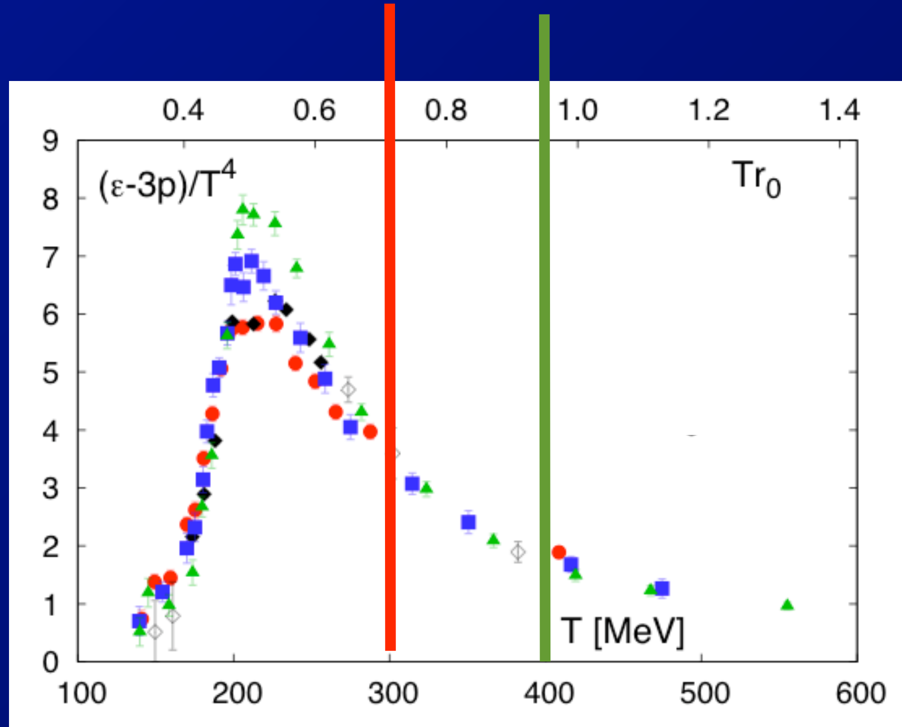
- Lattice thermodynamics from hotQCD group
  - ⇒QCD trace anomaly $(\varepsilon\text{-}3p)/T^4$
  - ⇒an “interaction measure”

Summary & Comments/Questions (3)

T_{RHIC} (τ =1fm) T_{LHC} (τ =1fm)

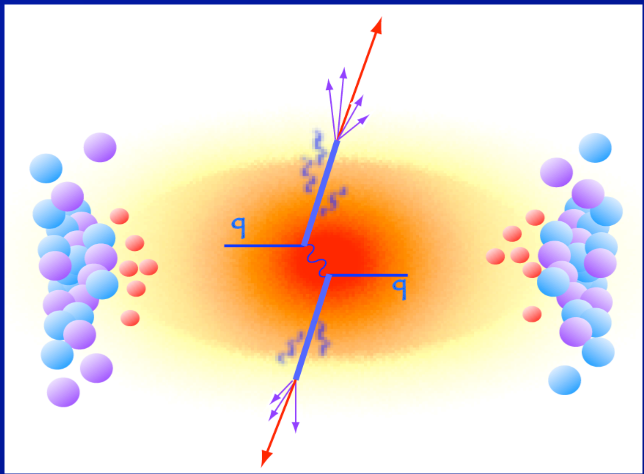
Energy Density or pressure

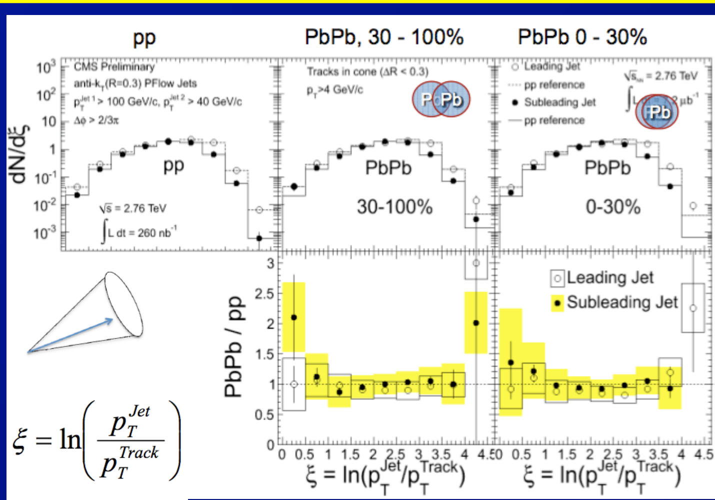


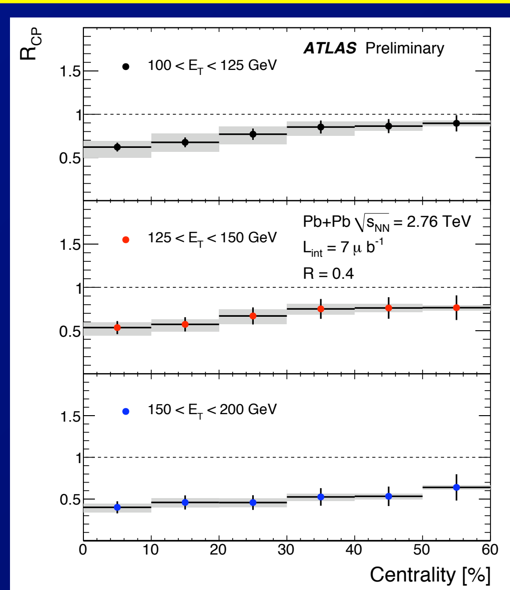


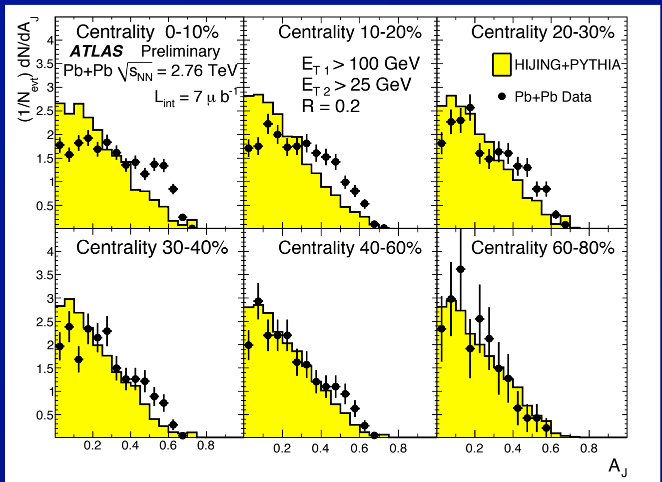
- Will we be able to “see” the effects of the higher temperature initial conditions using flow measurements at the LHC?

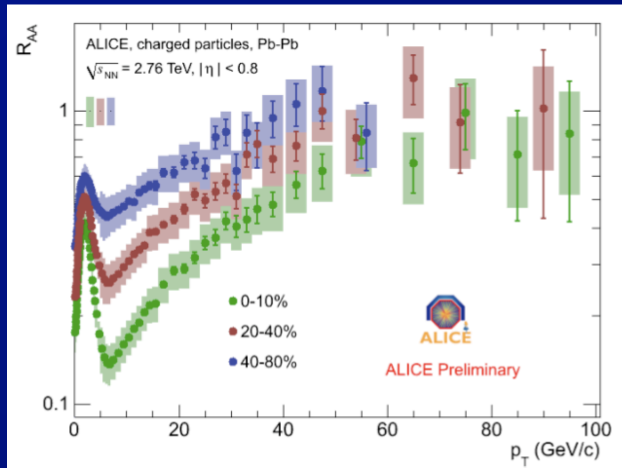
Summary & Comments/Questions (4)











- Rapid progress on high-p_T, jet physics program
- Possible physical picture emerging
  - Energy lost by jets appears at large angles wrt jet axis

⇒But, we are just at the beginning. Stay tuned.